Kolab: Improvising Nomadic Tangible User Interfaces in the Workplace for Co-Located Collaboration

Thesis

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Kolab: Improvising nomadic tangible user interfaces in the workplace for co-located collaboration.

By

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Abstract

Tangible User Interfaces (TUIs) [Ishii 1997] offer an interface style that couples *"digital information to everyday physical objects and environments"* [Ishii 1997 page 2]. However this physicality may also be a limitation as the tendency to use iconic representations for tangibles can result in inflexible *'concrete and specialised objects'* [Shaer 2009 page 107].

The current research investigates whether by reducing the dependence on specific tangible sets through the use of improvised tangibles we may begin to address the issue of tangible flexibility within TUIs. Improvised tangibles may be characterised by being potentially arbitrary and abstract, in that they may bear little or no resemblance to the underlying digital value. Core literature in the field (e.g. [Fitzmaurice 1996] [Ishii 2008] [Hornecker 2006] [Holmquist 1999]) suggests that a system based on improvised tangibles would suffer from impaired usability and so the research focuses on the impact on usability due to a lack of close *representational significance* [Ullmer 2000] during co-located collaboration.

Using a prototyping methodology a functional, shareable, TUI system was developed based on computer vision techniques using the Microsoft Kinect[Microsoft2011]. This prototype system ('Kolab') was used to explore an interaction design that supports the dynamic binding of improvised tangibles to digital values. A simple co-located collaborative task was developed using 'Kolab' and a user study was conducted to investigate the usability of the system in a collaborative context.

Within the limitations of the simple task the results of the study show that a) users appeared comfortable with improvising artefacts b) the high rate of task completion strongly suggests that a lack of close representational significance does not impair system usability and c) despite some temporary issues with users interfering with other's action an overall indication of equitable participation suggests that collaboration was not impaired by the 'Kolab' prototype.

1 Introduction

1.1 Rationale

A defining characteristic of Tangible User Interfaces or TUIs [Ishii 1997] is that they *"augment the real physical world by coupling digital information to everyday physical objects and environments"* [Ishii 1997 page 2]. The physical objects employed within a TUI are used to portray and manipulate digital data and from this emerges two properties unique to this style of interaction. Firstly, the physical objects provide a mechanism to *directly* manipulate the digital data such that there is a dedicated link between a physical object and its digital representation, this characterises a property known as *tangible manipulation* [Wellner 1991] or *direct manipulation* [Fitzmaurice 1996]. This *direct manipulation* contrasts with the operation of pointing devices such as a mouse which allow only indirect manipulation of data using a pointer [Fitzmaurice 1996]. Secondly, multiple physical objects can be operated simultaneously, which characterises a property known as *spatial-multiplexing* [Fitzmaurice 1996] whereby each object provides for a simultaneous access point into the system.

This combination of physicality and the potential for spatial multiplexing suggests that tangible user interfaces may be well suited to support face-to-face collaboration in at least two independent respects, from [Shaer 2009](Section 9.1) : firstly through the familiarity of the physical objects used in the interface and the possible actions on those objects that are readily perceived by a user of the objects (these possible actions are referred to as an object's *affordances* [Norman 2002]) and secondly, by providing multiple simultaneous access points which allow the interface to be shared simultaneously between users (such interfaces are often referred to as a *shareable* interface). However, physicality can itself give rise to limitations. For example the tendency to design physical objects as iconic representations of the underlying digital data can result in *'concrete and specialised objects'* [Shaer 2009 page 107]. Such *'specificness'*[Shaer 2009 page107] means that the physical objects cannot easily transform into different digital objects contributing to the premature commitment of model designs which makes later changes difficult. Ishii (in [Ishii 2008 page xvi]) sums up the issue of flexibility with the observation that a TUI is typically *"A special purpose interface for a specific application"*.

It is the case that many tangible devices that support co-located or face-to-face collaboration rely upon large fixed installations, for example 'URP' [Ullmer 2000] and 'Reactivision' [Kaltenbrunner 2007], but more flexible, general purpose *nomadic* tangible interfaces are beginning to emerge that support collaboration. Examples include 'Portico' [Avrahami 2011],'PlayAnywhere' [Wilson 2005], 'Docklamp' [Do-Lehn 2009b] and 'Bonfire'[Kane 2009]. Dalton, Mackay and Holland (in [Dalton2012]) use the term 'nomadic' to refer to devices that are portable (i.e. easily moved from place to place) but static when operated. However, even as TUI systems become more nomadic, one factor potentially limiting the portability and flexibility of such systems remains: namely that each system still requires fixed artefact sets (the physical objects used within a tangible user interface are referred to as tangibles, models, artefacts, tokens or token sets, this current work shall use the terms tangibles and artefacts interchangeably to refer to the physical objects used within a tangible interface).

The constraint of fixed tangible sets potentially inhibits the extent to which it is practical for nomadic general purpose tangible interfaces, designed using current approaches, to run multiple applications. With typical existing approaches multiple applications would require multiple sets of tangibles, for example 'Portico' [Avrahami 2011] requires a different set of artefacts per application, 'Docklamp' [Do-Lehn 2009b] requires pre-printed paper sheets and 'PlayAnywhere' [Wilson 2005] uses specially designed Perspex pucks and models. This conventional approach potentially limits the portability of these systems by requiring the specific tangible sets to be a) designed b) produced and c) transported with the system increasing the system's spatial extent or 'bulkiness' [Green 1998]. Also, at a practical level the tangible sets are prone to attrition by the

loss or mislaying of potentially critical tangibles [Shaer 2009](section 9.2.1) or simply getting mixed between applications [Avrahami 2011].

One solution is the ad-hoc labelling of everyday items to use as tangibles. This can be used to limit the need to transport specific tangible sets but this approach requires additional label printing [Cheng 2010] or RFID tagging equipment [Want 1999] to create and maintain the labels, replacing one set of equipment that must be transported and organised, sets of tangibles, with another, namely label writers and labels.

By contrast, the focus of this thesis is a system that takes advantage of the fact that the world is full of potential tangibles (see [Silver 2010] and [Brereton 2000]) and allows users to appropriate artefacts from the surrounding environment. The current research explores the design of a nomadic shareable tangible user interface ('Kolab') which realises the necessary interaction techniques that allow users to improvise the objects used as tangibles. In this thesis we shall refer to such tangibles as *improvised tangibles*. Improvised tangibles may be characterised by being a) potentially arbitrary b) abstract in that they may bear little or no resemblance to the underlying digital value and c) without any additional machine readable markings or labelling to assist object recognition and tracking.The use of improvised tangibles obviates the need for application specific tangible sets which, as discussed above, is a potential obstacle to the practical realisation of general purpose portable tangible devices.

1.2 Technology

As mentioned above, in order to conduct this current research a novel, nomadic tangible platform was prototyped. The 'Kolab' prototype is a computer vision based system that uses a single notebook computer and a combined colour and depth camera (Microsoft's "Kinect"[Microsoft 2011]) mounted on a tripod to create a multi-user touch-table upon which everyday items can be introduced, imparted with value, and arranged (see figure 1 below). The Kolab system has been developed to track objects across a work-surface and also to provide hand tracking and a portable touch table in a form available on any surface.

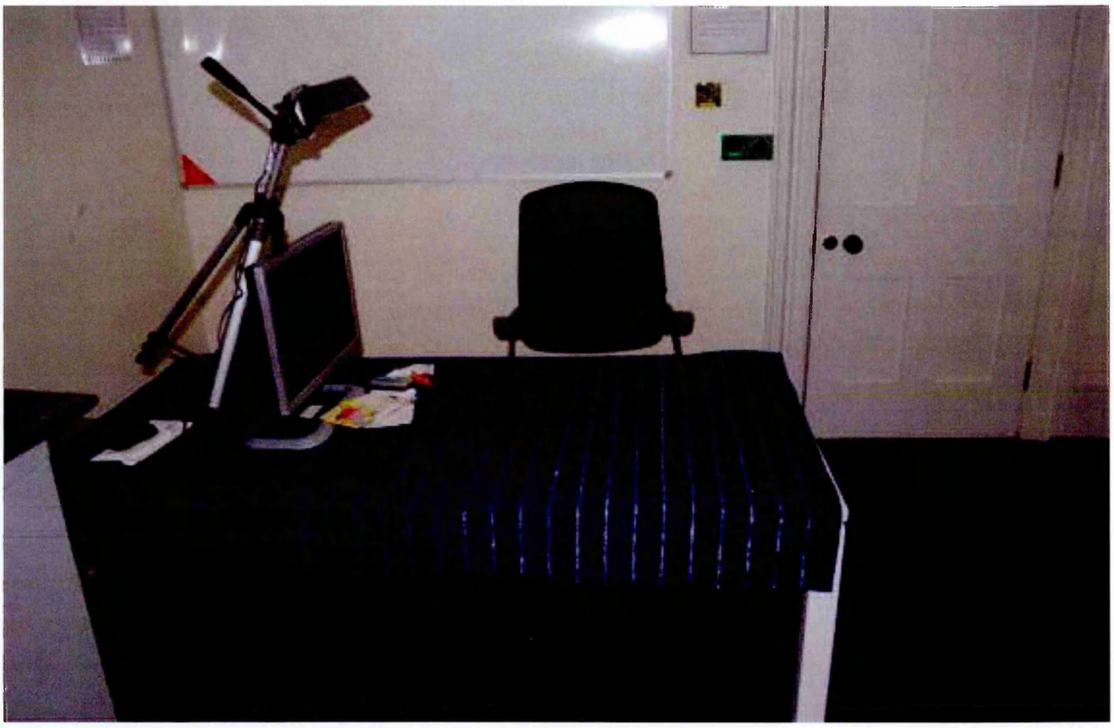


Figure 1 – Typical tabletop set up for Kolab.

1.3 Representational Significance

In order to provide context, it is useful to briefly review an issue from the TUI literature of particular relevance to the present thesis, namely that of *'representational significance'* [Ullmer 2000]. *'Representational significance'* is the degree to which the digital and physical forms match.

Work by Carvey, Gouldstone, Vedurumudi, Whiton and Ishii ([Carvey 2006]) and Cheng, Liang and Chen ([Cheng 2010]) has explored the use of improvised objects as controls in single user tangible interfaces but the use of improvised tangibles as both data and controls in a *multi-user* tangible user interface has generally been overlooked. Such a multi-user system may introduce usability problems due to the fact that the physical form of objects chosen by users may not resemble the underlying digital data. This lack of close representational significance may be particularly relevant in a multi-user system where the meaning of the objects needs to be shared. The implications of the lack of close representational significance are discussed in this section.

As discussed above in section 1.1, tangible user interfaces typically employ physical objects that closely resemble the underlying digital data. This leads to a lack of flexibility. Such specific models are often iconic and generally retain a close level of *'representational significance'* [Ullmer 2000] to the real-world object they represent. More precisely the term *'representational significance'* means that there is a degree of match between the digital data and the physical form, for example model buildings in an urban planning application [Ullmer 2000] and magnifying-glasses to represent zoom controls on a desktop [Ullmer 1997].

The tendency towards using iconic representations in TUI is re-enforced by the core literature within the field. Literature such as [Fitzmaurice 1996] and [Ishii 2008] strongly suggests that tangibles need to take on an *'explicit physical form'* [Ishii 2008 page 2]. Fitzmaurice (in [Fitzmaurice 1996]) requires *'strong specific'* tangibles as a basic property of graspable interfaces. As previously described, the Kolab system is a tangible interface based on potentially arbitrary user improvised tangibles which may not possess this apparently core characteristic of representational significance. The temporary nature of such improvised tangibles may be thought to diminish the tangible nature of an interface as suggested by Hornecker and Buur (in [Hornecker 2006]) and Holmquist, Redstrom and Ljungstrand (in [Holmquist 1999]). Hornecker and Buur suggest that the physical and digital representations in a TUI should be of the same strength and when considering the inter-relations between these representations report "that users perceive a tangible interface as *'not ' very tangible' and the tangible objects as insignificant, if these were only of temporary relevance or not expressive.'* " [Hornecker 2006 pp441]. This remark mirrors earlier work by Holmquist, Redstrom and Ljungstrand in [Holmquist 1999] which describes abstract containers as 'temporary...' in favour of more concrete 'tokens'.

Arias (in [Arias 2000 page 2]) describes the notion of boundary objects as objects with a shared understanding that '*serve to communicate and co-ordinate the perspectives of various communities*'. In a sharable interface such as TUI the tangibles may be considered to be boundary objects. When improvising tangibles the lack of explicit physical form may be particularly relevant in a multi-user or collaborative setting where users may need to share physical artefacts and importantly also share the understanding of those artefacts. It is possible that a lack of *representational significance* may impact collaboration, as the understanding of an improvised tangible may not be shared by all participants or the shared understanding may not be retained by all participants during the course of the collaboration.

These lines of argument put in question the usability of a shareable system based on improvised tangibles that have little or no resemblance to the underlying digital value.

1.4 Research Question

By reducing the dependence on specific sets of tangibles through improvisation we may begin to address the issue of artefact flexibility within tangible user interfaces (an issue discussed in Section 1.1). This may be especially relevant when considered in the context of nomadic computing as the reduction in bulkiness achieved by removing the need to transport multiple sets of tangibles may help alleviate some of the reported issues, for example mixing of specific tokens between applications in [Avrahami 2011]. This in turn may realise more portable, general purpose TUI systems based on more flexible sets of tangibles. Face-to-face or co-located collaboration is expected to be an area particularly suited to the use of tangible interfaces because of the physicality of the interface and the support for spatial multiplexing [Shaer 2009]. However as noted above the use of improvised tangibles in a collaborative context is worthy of investigation to examine the potential impact of tangibles with poor *representational significance*.

The above motivates the central research question as follows.

Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?

It is perhaps worth noting at this stage that within the context of this current research the term 'collaboration' is taken to mean 'working together towards a common goal'. Also, it is assumed that this working together occurs when participants are co-located and working at the same time to achieve this goal (i.e. face-to-face). This is in contrast to collaboration that may occur remotely (for example through video conferencing or email) or at different times (for instance sharing a shared surface such as a whiteboard between shifts).

In order to gather data to examine the research question, a necessary pre-requisite was to develop the Kolab system (outlined earlier in section 1.2) to provide a platform from which to explore the research question. A subsidiary research goal is to examine the issues and limitations of the interaction design of this system, with the aim of informing future TUIs that use improvised tangibles.

1.5 Methodology

To explore the idea of improvising tangibles a number of methodologies were considered. These were ethnographic observation, low-fidelity prototyping in the form of a 'Wizard-of-OZ' style system, and the development of a high-fidelity prototype; each of which will be defined and discussed in turn.

An ethnographic observation of the use of tangibles in natural conversation and problem solving would be a valid starting point for this current research but as mentioned in the literature review later this has already been done by Brereton and McGarry [Brereton 2000] in a study examining how engineers discuss problems and appropriate everyday objects to help illustrate engineering ideas to others.

This current research focusses on whether user acceptance and user interpretation of improvised tangibles is a limiting factor during collaborative interaction so it would seem natural to consider presenting users with a functional TUI to complete a task. To achieve this, a prototyping methodology was considered. Development of a prototype has the merit of allowing particular design issues or characteristics to be explored without committing to a fully functional product. Additionally, the prototype approach allows specific aspects of a design to be explored and modified quickly. A prototype may be low-fidelity, such as a 'Wizard-of-OZ' system where users interact with the software, but the responses are simulated by a human operator [Rogers 2011] or alternatively a prototype may be high-fidelity and incorporate a large amount of working features. Both options are discussed next.

Low-fidelity prototypes are useful in early stage designs and may possibly have been useful for exploring the user interaction design of Kolab however this would not necessarily address the investigation of an image processing system to track multiple objects. Computer vision systems are often sensitive to the object sets they are developed to track and also the environment in which they operate. For instance when considering the object sets that may be presented the object recognition and tracking schemes require a known set of features to extract from an image in order to identify and follow objects across image frames. This set of features is known as a feature vector and may include object characteristics such as shape and colour. The more specific this feature vector is to the object set the more reliable recognition and tracking can be made. Also when considering the operating environment of a computer vision system lighting conditions can play a major part in the success of such a system. Even subtle changes in ambient lighting can be a major factor in the performance of many vision systems as this may change the overall contrast of a scene, change the intensity of shadows and reflections, and may radically change the colour shades detected by a camera. As such, any real TUI system based on computer vision would make compromises and users would have to be exposed to these limitations. For this reason a low-fidelity prototype 'Wizard-of-OZ' system was rejected in favour of a system with more functionality to allow such limitations to emerge during the research.

From the perspective of the early stage of this project we needed to approach the problem on two fronts. Firstly, 'bottom up' to investigate whether a vision processing system observes and tracks individual improvised tangibles (and if so what are its limitations) and 'top down' - are users willing and able to use improvised tangibles to perform some task or computational process? To address these two approaches the process of rapid prototyping was considered using a high fidelity functional prototype. Such a prototype would allow the realisation and exploration of a suitable user interaction design as well investigating the limitations of a sophisticated object tracking system based on computer vision.

The chosen methodology used during the research was one of high-fidelity prototyping. Chapter 3 describes the Kolab prototype in detail. The software prototype enabled a formal user study to be conducted in which users were asked to complete a collaborative task using improvised tangibles.

Prior to designing the formal user study, the research question outlined above (in section 1.4) was refined to accommodate a more detailed exploration of the research issues. This refinement involved restating the research question as a series of more detailed 'operationalised' questions. In this form, the questions were more readily able to be evaluated in a user study. These refined and expanded research questions are described further in Chapter 4.

The user study, described in detail in Chapter 5, was a cross-sectional, between-subjects study. This means that all participants used the system and there was no control group. The users participated in pairs enabling the maximum number of collaborative sessions to take place, at the expense of the number of users in each session.

The user study was an in-situ study. More specifically, the study was conducted in a meeting room within an office building rather than a laboratory or room designed for user studies. It was envisaged that such meeting rooms and meeting spaces would be representative operating environments for a system such as Kolab.

The task users were asked to perform during the user study was derived from a team-building exercise known as 'Lost at Sea'. This choice of task represented a practical decision regarding task complexity such that users could readily engage in a meaningful way with a novel system and perform what was asked of them within the time constraints of a busy working day. Although engaging, the task that did not require specific domain knowledge from participants and could be completed in the allotted time. The same task was used during the prototype testing stage. The task is described in detail in in Chapter 3.

The main form of data capture from the user study, aside from video of the sessions, was a user questionnaire based on the SUS [Brooke 1996]. The SUS methodology was chosen because it is widely used [Sauro 2011], free and a short but effective way to capture user responses in a structured way while providing a quantitative measure of usability; section 2.6.1 describes the SUS methodology further. The SUS was modified to add a 'Notes' sections after each question. This provided space for richer responses beyond the 1-5 range Likert scale responses of the SUS.

Recall that Kolab is a prototype platform intended to support collaborative work; and as such, part of the user study was used to explore the extent to which the Kolab prototype encourages (or at any rate avoids prohibiting) collaborative behaviour. To explore the extent to which collaborative behaviour was encouraged during the user study, the user survey included two additional questions to indicate each participant's view of both their overall participation in the solution and that of their partner's. This choice was suggested by issues identified by Marshall, Hornecker, Morris, Dalton and Rogers in [Marshall 2008]. When considering sharable interfaces Marshall et al [Marshall 2008] identifies equitable participation as a generally desirable situation for cooperative working. Equitable participation may depend on many factors, for instance Marshall et al demonstrates how the design of entry points to a system can influence levels of participation. Consequently, a simple indicator of participation levels was added to the user study questionnaire in order to identify the extent to which collaboration is facilitated. If a participant views his/her level of input to a solution as the same as his/her partner then we can infer that the session was conducted in a broadly collaborative and cooperative manner.

Other data capture methods used during the user study were in-room video and open questions to participants, asking them to describe their experience during the user study session.

As a supplement to the user study sessions and SUS survey described, an email survey was carried out. A small questionnaire was emailed to the study participants to investigate what items may have been brought into the study sessions by participant but were not used during the session.

The user study, results and conclusions presented within this current document form the basis for a paper by Dalton, Mackay and Holland [Dalton 2012] which was presented at the 'ACM Designing Interactive Systems Conference 2012' (www.dis2012.org) in June 2012.

2 Literature Review

This chapter begins with a brief history of the development of TUI and describes common characteristics of this interface style. After we characterise a tangible user interface we go on to present a number of frameworks which enable apparently different tangible interfaces to be compared, these frameworks are used later in chapter 3 to describe Kolab.

After this general background we move on to consider the potential strengths and weaknesses of tangible interfaces (section 2.3) with a focus on the issues of flexibility and representational significance which is of particular relevance to our central research question. Having considered potential issues with the physicality of the interface, section 2.3 also examines the impact of accommodating multiple users by looking at the possible effects of 'multiple access points' on user behaviour as this is relevant to the interaction design presented in chapter 3. The discussion of TUI concludes with a survey of related studies and previous work (sections 2.4 and 2.5) in order to 'place' the current research within the state-of-the-art.

The chapter ends with some background on an evaluation method used in the formal user study.

2.1 TUI Characteristics

Tangible manipulation is a key characteristic of a TUI and is a form of human-computer interaction in which users manipulate digital and physical data directly by touch. The term was first used by Wellner and is illustrated by The Digital Desk system [Wellner 1991]. The Digital Desk allowed users to bring paper to the desk and used overhead cameras to track the user's finger and scan the content of the paper indicated by the user's finger. The text indicated by the finger was converted into digital data for use in a calculator application projected onto the user's desktop. The cameras and hand tracking also meant that a user could interact directly with the digital calculator.

The Digital Desk idea introduced a desktop upon which data on a physical medium can be combined with digital data to blur the physical-digital boundary. This idea was taken further by Fitzmaurice [Fitzmaurice 1996] who introduced the *'graspable'* interface. The 'graspable' interface demonstrated the physical manipulation of digital data using deformable 'bricks' on a large desktop display. By employing multiple bricks the 'graspable' user interface allowed *multiple* physical objects to directly manipulate computer data on-screen. Fitzmaurice's 'direct manipulation' is similar to Wellner's idea of 'tangible manipulation' [Wellner 1991] in that physical objects are directly bound to corresponding digital data; manipulating a physical object directly affects its digital counterpart. This contrasts with the operation of pointing devices such as a mouse which only support the in-direct manipulation of data through the use of an on-screen pointer. In this current research the term 'tangible manipulation' will be used in preference to 'direct manipulation'. As well as supporting tangible or *direct manipulation* of the data, Fitzmaurice's graspable interface also introduced the characteristic of *'spatial multiplexing'* whereby each object provides for a simultaneous access point in to the system. Fitzmaurice observed that having multiple objects, each potentially operating independently, means that interactions are not limited by the sequences of actions that a mouse imposes (*'time-multiplexing'*).

Both Wellner (in [Wellner 1991]) and Fitzmaurice (in [Fitzmaurice 1996]) presented single user tangible systems; Arias and Eden [Arias 1997] took this a stage further and combined *'physical and computational media'* to support design tasks for multiple users. Arias and Eden provided a sharable table with graspable, movable tiles to allow different stakeholders to participate in an urban planning activity around a table in parallel. Their aim was to explore the interactions of the users not only with the system but with each other.

All three of these systems explored the two basic characteristics of tangible user interfaces – a physical interface supporting *tangible manipulation* and *spatial multiplexing*. To summarise these important terms; in a tangible user interface, users can operate the systems with two hands picking up, moving and examining items as required. This is referred to as *'tangible manipulation'* ([Wellner 1991]). The term *'spatial multiplexing'* was coined in [Fitzmaurice 1996]; in a spatially multiplexed system each tangible has its own space and dedicated channel into the underlying system. This means that each physical object can operate in parallel around the workspace rather than having a single device controlling multiple functions. Importantly, the property of spatial-multiplexing gives rise to the ability of a TUI to be a *shareable interface* as demonstrated in [Arias 1997]. This means that TUI can accommodate multiple users operating a system concurrently through multiple access points into a system. We will examine the implications of multiple access points in section 2.3.2.

Taking together the ideas of *'tangible manipulation'* ([Wellner 1991]), *'space-multiplexing'* ([Fitzmaurice 1996]) and shareable tangible interfaces, Ishii and Ullmer, in [Ishii 1997], envisaged systems where both data *and* controls were represented by physical objects and introduced the term *'Tangible User Interface'* or TUI [Ishii 1997].

In order to help characterise the features of a TUI system further Ullmer and Ishii, in [Ullmer 2000], drew upon the 'Model/View/Controller' software design pattern (MVC). In the TUI version of the MVC pattern the *controller* is the physical world and the objects that make up the physical artefacts of a TUI; the *model* is the underlying computer system which couples the physical objects to the digital representations; and the *view* (or 'output space') is split between the physical and digital representations. By using this design pattern Ullmer and Ishii established the core features of a TUI system: physical objects bound to digital representations; direct manipulation of the objects resulting in manipulation of the digital realm and real-time feedback of the results of the interactions.

Three further examples of TUI in a variety of forms are presented next to help illustrate how these core features may be realised; these are firstly Bishop's Marble Answering Machine [Ishii 1997] which is an example of the use of abstract artefacts to represent objects combined with physical constraints used to define functions. Secondly, 'metaDesk' [Ullmer 1997] which follows on from Wellner's 'Digital Desk' [Wellner 1991] and Fitzmaurice's 'Bricks' [Fitzmaurice 1996] as a desktop style interface. Finally, URP [Ullmer 2000] illustrates a sharable, tabletop style tangible user interface.

The Marble Answering Machine [Ishii 1997] is a prototype telephone answering machine integrating everyday objects with computers. Incoming messages are physically instantiated as marbles, by dropping a marble in a specific indentation the message is played and placing a marble in an augmented telephone the call is returned. This illustrates the use of everyday objects as graspable artefacts within a TUI and shows how devices can be very application specific, a theme that it is picked up further in section 2.3.

'metaDesk' [Ullmer 1997] is an extended desktop similar to [Wellner 1991] and [Fitzmaurice 1996] but is enhanced with physical or *tangible* objects called 'phicons' and 'phandles'. Perspex 'phicons' (<u>ph</u>ysical <u>icons</u>) represent data objects and 'phandle' controls (<u>ph</u>ysical <u>handles</u>) represent controls to directly manipulate digital information presented on a back-projected desktop surface. The 'phicons' are physical representations of common GUI elements and models of objects for instance a 'lens' phicon represents a window of data with a 'magnifying glass' phicon to 'zoom' in and out, other models are iconic representations of application specific things such as buildings . Borrowing from the 'Bricks' concept of handles (from [Fitzmaurice 1996]) the 'phandles' may be used to grab and manipulate data. The 'geoSpace' application on the 'metaDesk' illustrates its operation. A model ('phicon') which represents a building on the MIT campus can be placed on the desk display showing a campus map and the map is centred on that building , if a second building model is placed on the map the map scales to fit both on, rotating the buildings rotates the underlying maps. An additional 'lens' control allows other areas of the map to be called up in a secondary display.

Finally, 'URP' [Ullmer 2000] allows physical models of buildings to be placed on a table-top surface representing a street-map. It is a shareable interface allowing multiple designers to physically arrange the model buildings on the surface. Using physical controls such as a clock and a wind-strength weather vane users can change parameters in the system to see the impact of the building design on ambient light and wind-flow as the day progressed; the system projects shadows onto the table-top as the 'clock' control changed the time of day and showed wind-flow through the buildings by projecting a display of arrows.

As we can see from the examples above tangible user interfaces are physical interfaces, but crucially the physical objects that comprise them embody in some way both the data and controls for the associated virtual world. For example, the houses in 'URP' [Ullmer 2000] embody digital data and the magnifying glass in 'metaDesk' [Ullmer 1997] along with the wind and time controls in URP embody digital controls. Furthermore, the *'explicit physical form'* [Ishii 2008 page 2] of such interaction objects typically suggest the actions or effects they will have within the digital system. The physical forms of such objects and the actions this form suggests are often referred to as their *affordances* [Norman 2002]. A key feature of this kind of interface is that interaction with the objects directly affects their digital equivalents in the underlying system (*'direct manipulation'*). Importantly, there is immediate real-time feedback of the results of the interaction delivered in the same location as the objects (*'coincidence of input and output space'* [Iishi 2008 page xxi]). A familiar but non-digital example of full coincidence is the abacus. The abacus is neither an input nor an output device, but both simultaneously; the Marble Answering Machine introduced above is a digital example of full-coincidence.

To summarise, the common feature of all these examples is the realisation of Wellner's *tangible manipulation* and Fitzmaurice's *direct manipulation* through the three features anticipated by the MVC pattern discussed above; these features are the binding of physical objects to an underlying digital representations; the direct manipulation of the digital data through the manipulation of the physical objects; and the real-time feedback of the results of the manipulation. It is worth noting that, as these examples show, although *spatial multiplexing* is a characteristic of TUI, it is not a necessary feature of every TUI interface.

From the limited examples in this section it can be seen that there is a wide variety of possible interfaces that may be classed as tangible user interfaces each with their own unique features and characteristics. This variety has led to a number of frameworks being developed to help describe the common features of this style of interface in more detail and to enable comparisons between systems. A number of these frameworks are presented in the following section.

2.2 Descriptive Frameworks

Recall from section 2.1, that in a TUI has the following three characteristics: physical objects bound to digital representations; direct manipulation of the digital data; and real-time feedback. These characteristics may manifest themselves in a variety of ways as illustrated by the examples in sections 2.1 and 2.5; to help with the comparison between apparently different systems a number of frameworks have been developed to help describe these characteristics in more detail. In this section we consider the predominant frameworks in the field; these frameworks were used to inform the design of Kolab and are used later in section 3.5 to provide a brief description of the Kolab design with reference back to the literature.

We consider frameworks from Fishkin [Fishkin 2004], Edge and Blackwell [Edge 2006b] [Edge 2006a] , Ullmer, Ishii and Jacob [Ullmer 2005] and Shaer, Leland, Calvillo-Gamez and Jacob [Shaer 2004] which each describe the tangible interface in subtly different ways and we introduce the idea of tangible *interaction* from Hornecker and Buur [Hornecker 2006] and Jacob, Girouard and

Hirshfield [Jacob 2008]. Tangible *interaction* examines a tangible interface and its place within the surrounding environment with particular consideration to spatial interaction which is relevant to Kolab's use of gestures as part of the user interface. The application of metaphor and innate image-schema in the context of tangible interaction from Hurtienne and Isreal [Hurtienne 2007] is also introduced.

Fishkin [Fishkin 2004] suggests a two axis approach to characterising TUI systems. The axes are labelled 'Metaphor' and 'Embodiment', for reasons explained below. This approach presupposes direct manipulation and explicit physical form in the interface as well as some feedback or behaviour resulting from the manipulation. Fishkin's approach starts by measuring the 'tangibility' of the system. The degree of tangibility is quantified by categorising the level to which the physical forms (viewed as noun metaphors) and affordances (viewed as verb metaphors) embody or represent the properties and effects on the underlying digital object. The degree of tangibility measured in this way is used to assign a position on the 'Metaphor' axis. To assign a position on the 'Embodiment axis', the level of *coincidence of the input/output space* is considered. The framework provides *categories* to sub-divide the axes; Metaphor is taken to have sub-categories none, noun, verb or both; and Embodiment is taken to have subcategories full, nearby, environmental and distant. (The category 'environmental' is similar to Iishi's '*Intangible Representations*' [Ishii 2008 page xvii]). To illustrate Fishkin's taxonomy we re-visit URP (see section 2.1). URP illustrates both verb and noun metaphor. The model buildings illustrate noun metaphor – the buildings in UPR are like real buildings. Moving a model building in URP has a similar effect to moving a real building – this illustrates a verb metaphor. In the case of URP when the 3D models of buildings are moved on the surface the resulting shadows move accordingly. The real-time recalculation and display of shadows on the same surface as the buildings shows 'nearby' embodiment of output. The system's output (shadows) is shown close to the input (buildings).

Whilst Fishkin [Fishkin 2004] uses two dimensions to describe tangible user interfaces Edge and Blackwell[Edge 2006b] [Edge 2006a] apply 13 'cognitive dimensions' [Green 1998]. Cognitive dimensions are concepts or properties of a system that affect the mental aspects of usability and learning. This approach offers many dimensions to examine and discuss elements of usability. However, of these dimensions, particularly appropriate to the discussion about **Kolab** are the dimensions of v*iscosity* and *bulkiness* as they provide a useful terminology. *Viscosity* is the cognitive dimension measuring resistance to change, and this can be further divided in rigidity, the resistance to reconfiguration and rootedness, the resistance to movement. B*ulkiness* is the spatial extent of the system, in three dimensions.

Propounding a subtly different perspective, Ullmer et al [Ullmer 2005] as well as Shaer, Leland, Calvillo-Gamez and Jacob [Shaer 2004] describe a TUI system as a combination of physical artefacts representing digital information or a control, referred to as a digital variable, and other items that place physical constraints on the artefact. Ullmer et al refers to this as a TUI system based on '*token+constraint*[s]' [Ullmer 2005], similarly Shear et al describes such a TUI as employing the 'Token and Constraints (TAC) Paradigm' [Shaer 2004]. The manipulation of the digital variable is controlled by the physical affordances of the tangible (or *token* to use terminology from [Ullmer 2005] and [Shaer 2004]) and the constraints placed upon it. The manipulations of the tangible with respect to the related constraints have computational significance and result in behaviour within the system. Both Ullmer's and Shaer's perspective can be illustrated by the Tangible Query Interface [Ullmer 2003]. In this case, the tangibles are dial controls which are linked to specific query parameters. These tangibles are arranged in a rack which imposes a *physical or positional constraint* and the order and spacing of the tangibles (*proximity constraint*) indicates conditional logical for use in the query.

The approaches described so far focus primarily on describing the characteristics of the tangible interface: in other words, they consider the artefacts employed; the constraints upon them and the embodiment of feedback. The inherent physicality of the TUI style means that *"...interaction* *takes place in the physical world*" [Ishii 2008 page xv] and a number of frameworks have been developed which consider how users employ their natural motor and sensory skills to interact with a tangible user interface and also how a tangible user interface is incorporated into the users' environment. This is referred to as tangible *interaction*. The main frameworks for tangible *interaction* are [Hornecker 2006], [Jacobs 2008] and [Hurtienne 2007] each of which is presented below.

Hornecker and Buur [Hornecker 2006] show that tangible *interaction* centres on the body as the input device and the 'social affordances' of tangible interactions. The framework has four main themes under which systems may be analysed and described. There is a significant element of '*tangible manipulation*' which is similar to the frameworks already presented but in [Hornecker 2006] Hornecker and Buur also look beyond the tangible systems themselves to consider the '*spatial interaction*' of users' bodies with the system and each other, as they see what others are doing within '*spatial constraints*'; these are similar to constraints in the TAC paradigm [Shaer 2004] (described above) but with a wider view to consider the constraints imposed on users by the physical setup, e.g. access points, and the ability to tailor the environment to encourage interaction. The fourth aspect of this framework, *expressive representation*, considers the physical representation of digital data and controls. A part of this theme considers representational significance and so further discussion is deferred until section 2.3 when we discuss representational significance. As an aside on ways in which these frameworks can be further developed, work such as [Jota 2011] and [Hillages 2009] illustrates how the ideas of touch computing may be combined with additional interactions from free-air gestures above the surface and demonstrates how this wider 'spatial' view of the interface is beginning to gain interest.

Various more 'body-centric' frameworks provide additional useful perspectives. For example, whilst Hornecker and Buur [Hornecker 2006] takes a view of the body as the input device as part of a wider framework, Jacobs, Girouard and Hirshfield [Jacob 2008] in Reality Based Interaction (RBI) examine Human Computer Interaction (HCI) *exclusively* from the perspective of human awareness and skills. The RBI framework is has four themes – Naïve Physics (NP), Social Acceptance Skills (SAS), Body Awareness and Skills (BAS) and Environmental Awareness (EA).

The themes of Naïve Physics (NP), Environmental Awareness Skills (EAS) and Body Awareness and Skills (BAS) combine to something close to 'tangible manipulation' discussed earlier. These themes illustrate how the basic interactions with a TUI (for example adding, removing and rearranging artefacts) rely on a user's awareness of her surroundings and her own abilities to manipulate the interface. The 'Social Acceptance Skills' (SAS) theme helps to describe systems such as shared table-tops where users can leverage awareness of others in verbal and non-verbal forms; this is not especially relevant to the current research but the problems that may arise with sharable interfaces are picked up later in section 2.3.

The idea of body awareness is also taken up by Hurtienne and Isreal [Hurtienne 2007] which suggests that tangible user interfaces benefit from users applying pre-existing *'sensorimotor'* knowledge unconsciously which, according to Hurtienne and Isreal helps explain the intuitiveness of this interface style. Such pre-existing knowledge is described by image-schema, which are *'abstract representations of bodily interactions'.* For example, space schemas relate to movement-associated concepts such as up-down and near-far, while containment schemas describe constraints such as in-out and 'surface'. Hurtienne and Isreal propose that reasoning with such schemas is intuitive, and suggests that by the exploitation of simple metaphorical extensions to such schema, it may be particularly intuitive for users to operate tangible interfaces. For example the 'container' image schema may by extension become an intuitive constraint – items are on the table and need to remain on the table to be usable within the system.

We will return to these frameworks in Chapter 3 and use them to describe the **Kolab** system.

Section 2.1 outlined the general characteristics of a TUI and section 2.2 provided an overview of various frameworks which attempt to describe the variety of TUI systems in a standard ways. We now move on to look at the potential benefits and problems with TUI with particular reference to the issue of artefact flexibility and the possible consequences of using improvised tangibles in place of fixed iconic artefacts in the interface. As well as considering the problems introduced by using physical objects in the interface, we also look at the impact of spatial multiplexing. As previously mentioned spatial multiplexing allows for multiple access points and the impact of this feature is considered by looking at a number of studies which show how the configuration of the access points to an interface can influence user behaviour – an important consideration for TUI design in general and the interaction design for Kolab in particular (See Chapter 3).

2.3 The potential benefits and issues of TUI

The potential benefits of TUI arise from its inherently physical interface, and the support for multiple access points through spatial-multiplexing (these ideas were discussed earlier in section 2.1). The physicality of the interface may also be a limitation as the tendency towards using iconic representations of objects potentially limits tangible user interfaces by 'fixing' the representations of the underlying digital construct. Overcoming this limitation is a primary motivation for the current research.

In this section we examine the issue of flexibility with the physical interface and discuss the potential issue of using improvised tangibles in place of iconic representations (section 2.3.1). The impact of spatial-multiplexing offering multiple-access points is also discussed here as this may have a considerable impact on sharable system design (section 2.3.2).

2.3.1 The physical nature of TUI

Shaer and Hornecker [Shaer 2009] suggest the physical nature of a tangible user interface improves the directness of input by providing haptic feedback and the engagement of users' natural skills to manipulate objects, this is also discussed by Jacob, Girouard and Hirshfield [Jacob

2008] as 'Naïve Physics' (see section 2.2). Additionally, the physical engagement of users in the interface is also thought to encourage richer thinking by supporting epistemic actions and improved accuracy for some manipulation and acquisition tasks [Tuddenham 2010]. To achieve these potential benefits, a tangible user interface needs to provide physical objects with which users may interact in order to manipulate the underlying digital representations.

A common solution to this is to provide iconic representations of the underlying data, for instance model buildings in a planning application ('URP' [Ullmer 2000]) or brush type devices to represent paint brushes (I/O Brush [Ryokai 2004]). By leveraging the affordances [Norman 2002], constraints and familiarity of iconic models or physical devices, the physicality of tangible user interfaces potentially helps reduce the time to learn and engage with a system by designing application specific artefacts and inviting interaction and exploration. An example of such a system is 'I/O Brush' [Ryokai 2004] where the brush-like device used may quickly suggest the device's function as an electronic paint brush. Whilst providing an engaging experience the models used in these examples are fixed early in the system design phase and cannot change before or during the interaction. This presents the problem of 'fixed-ness' of representation and as noted by Hurtienne and Isreal [Hurtienne 2007, pg129] this has perhaps lead to *"too strong a reliance on physical one to one mappings in the majority of current tangible interfaces"*. It is the impact of this lack of flexibility we explore further in this section.

One useful way of exploring issues of flexibility in TUIs is to apply concepts drawn from the 'cognitive dimensions' approach noted earlier in section 2.2. For example, the dimension of lack of versatility or *viscosity* [Green 1998] can be used to highlight potential issues with TUI style interfaces. A case in point is that when physical objects with a fixed shapes are used in TUIs as models to represent views of an underlying concept (e.g. a house in URP), the fixed shape can obstruct certain operations, such as 'zooming' or changing the level of representation to change levels of detail. Other cognitive dimensions such as 'premature *commitment'* [Green 1998] highlight possible pitfalls that can occur when substantial design effort is expended before users

get experience of the system. Too much design work in advance of informal user testing may be wasted effort; premature commitment may not be problematic if designs are easy to change. A key consideration here is the already mentioned cognitive dimension of '*viscosity*' [Green 1998], which identifies systems that are difficult to change.

Lack of flexibility can be analysed from many other perspectives. Shaer and Hornecker [Shaer 2009 section 9.2.2] argue that fixed models or direct input can make solving complex tasks more difficult, and Ishii [Ishii 2008] identifies the need to balance the specific with the abstract. He argues in the context of the systems Illuminated Clay and Sandscape that '*A fundamental limitation of previous TUIs was the lack of capability to change the form of the tangible representations during the interactions*'[Ishii 2008 page xix]. The key point here is that fixed physical items are not physically malleable.

Jacobs et al. [Jacob 2008] note the related trade-off of reality vs. versatility in their discussions of RBI system design. On another related note, Arias and Eden [Arias 1997] observe that '*models are passive*'.

Leaving arguments about flexibility aside, there are practical disadvantages to the use of bespoke or specific physical objects as part of the user interface. Over time these models may get broken or lost and need replacing [Shaer 2009] or users may simply mix up sets of tangibles, as demonstrated in 'Portico' [Avrahami 2011] this may result in applications failing to work correctly. Also with specific reference to multi-application nomadic devices, as previously mentioned in Chapter 1, and illustrated further in section 2.5, under typical existing approaches to tangible interface design, multiple applications require multiple sets of tangibles. This approach potentially limits the portability of such systems by requiring the sets of tangibles to be transported along with the device. Edge and Blackwell [Edge 2006a] and Green and Blackwell [Green 1998] refer to this as *bulkiness* and describe it as a property that characterises the spatial extent of a system.

A potential solution to the issues of *viscosity* and *bulkiness* is the use of objects from the local environment to act as tangible artefacts. By using such improvised tangibles, there is no need for them to be transported with the system. This solution is novel in co-located collaborative settings but other studies have shown that users are willing to use more abstract improvised objects as elements of single-user computer interaction for example 'Amphibian' [Carvey 2006], 'GlowDoodle'[Silver 2010] and 'I/O Brush' [Ryokai 2004] or as thinking props in meetings [Brereton 2000] to help illustrate ideas. Additionally [Edge 2009], [Carvey 2006] and [Cheng 2010] are TUI studies which include examinations on how users organise their desks, and from these studies it can be seen that a typical work area is filled with potential artefacts which we can use to connect our digital and physical worlds.

The work described above suggests that improvisation of tangible artefacts by selecting objects from the local environment is a potential solution to the problems of flexibility and bulkiness however suitable interaction techniques are required so that the chosen objects can be dynamically associated at run-time to underlying digital data – this is addressed in Chapter 3 . Also, by using improvised tangibles in a collaborative setting and by removing the close representation of the artefacts to the underlying digital values we may introduce usability issues as alluded to in chapter 1. This potential lack of close *representational significance* [Ullmer 2000] is discussed next.

2.3.1.1 Representational Significance

The need to have a close degree of match between the digital data and its physical form is a strong feature of the theoretical background when defining tangible user interfaces. Ullmer and Ishii (in [Ullmer 2000]) describe this degree of match as '*representational significance*'.

Early work by Fitzmaurice [Fitzmaurice 1996] differentiates between 'weak general' and 'strong specific' tokens to the extent that he defines a 'strong specific' token as a basic property of a graspable interface. Similarly, Holmquist, Redstrom and Ljungstrand [Holmquist 1999] differentiate between 'containers' and 'tokens'. The latter need *'physically resemble the information they represent in some way'* [Holmquist 1999 page236] whilst the containers are a temporary store of little relevance. These early characterisations of tangible interfaces show how the apparent need for a close degree of match between the digital data and its physical form is a strong feature of the design literature. This idea has carried through the core literature in the field which strongly suggests that artefacts need take on *'explicit physical form'* [Ishii 2008] and that the *'representational significance'* [Ullmer 2000] of a physical artefact (or phicon) is a vital part of its representational legibility for users. Examples of such 'phicons' include model buildings in an urban planning application [Ullmer 2000] and magnifying-glasses to represent zoom controls on a desktop [Ullmer 1997]. The idea that the legibility of tangibles may affect usability is re-enforced by Hornecker and Burr [Hornecker 2006]. When discussing representational significance (as part of the 'Expressive Representation' theme of the Tangible Interaction framework) Hornecker and Burr suggest that the physical and digital representations should be of the same strength and when considering the inter-relations between these representations report "that users perceive a tangible interface as *'not ' very tangible' and the tangible objects as insignificant, if these were only of temporary relevance or not expressive.'* " [Hornecker 2006 pp441].

In [Baskinger2010], Baskinger and Gross perhaps sum up the apparent importance of representational significance by presenting tangible interaction as a combination of computing (meaning digital technology or software) and physical form. In [Baskinger2010] physical form is seen as key to establishing the role of an artefact within the interaction *"as it visually signals and physically embodies functionality, expresses cues for understanding, and provides the script for interaction"* [Baskinger2010 page 8] and it is the design of this form that *" establishes the roles an artifact will play.* "[Baskinger2010 page 6] - From this it seems that abstract form may hinder establishing the role of an artefact in an interaction.

As can be seen from the work above the need for a strong relationship between the physical appearances of real-world artefacts to the underlying digital data appears as a core characteristic of a tangible user interface. This raises the question of the usability of a tangible user interface based on items with little or no representational significance. It is this question that is central to the current research because if the problem of TUI flexibility is to be overcome by supporting improvised tangibles then the impact of poor representational significance on system usability must also be considered. It is worth noting at this stage that, as discussed by Jacobs et al in [Jacobs 2008], there is a trade-off in interaction design between 'reality' and such considerations as expressive power and versatility. In the context of this current research this means we would not suggest that a system without strong representational significance is expected to be un-usable but rather we would expect to see diminished system usability as we trade-off representational significance for artefact flexibility.

This concludes the discussion around the physical objects used in a tangible user interface for *tangible manipulation*. Recall from 2.1 that a TUI has a second distinct characteristic – that of *spatial multiplexing* which refers to the multiple access channels available when using multiple tangible artefacts. This current research is not focussed on exploring this particular characteristic of TUI systems. However, it must be considered as part of the interaction design for Kolab, as studies have shown that a number of problems emerge when interfaces become shareable. It is especially relevant here as Kolab requires interaction techniques to support the dynamic binding of the improvised objects to the required underlying digital values, and so needs to consider the impact of multiple control channels; this is to ensure that the potential benefits of improvised tangibles are not undermined by inappropriate interaction design. The potential issues introduced by sharable interfaces are discussed in the next section as background for the interaction design presented in Chapter 3.

2.3.2 The impact of multiple access points on user interaction

As discussed earlier in section 2.1, tangible user interfaces support spatial multiplexing [Fitzmaurice 1996]. This means that artefacts may be manipulated simultaneously, effectively creating multiple access points into the system, Ishii and Ullmer [Ishii 1997 page 11] refer to these as *'many loci of physical control'*.

There appears to be little research specifically examining the impact of spatial-multiplexing on user interaction in tangible user interfaces but many TUI systems are based around some form of surface or table, for example [Ullmer 2000] , [Arias 1997] and [Klemmer 2000]. This style of TUI, referred to as *Tangible Tabletop Interaction* [Shaer 2009, section 3.1.2] or *'Interactive Surfaces – Tabletop TUI'* [Ishii 2008 page xix], makes them similar to other sharable interfaces, such as touch surfaces, for which there is a wide body of research into the impact of multiple access points on user interaction. As will be shown, the configuration and number of access points can have an impact upon the user interaction, and so this feature of TUI has a particular relevance when considering system design of sharable systems – not just tangible user interfaces.

Providing an environment for co-located collaboration allows for users to increase their awareness of other participants, and of the overall state of the surface. Being face-to-face offers unique opportunities to communicate during collaborations, as demonstrated in [Fleck 2009] and [Arias 1997], which show how verbal and non-verbal interactions (*language and actions*) are used to develop, organise and negotiate solutions. Rogers, Lim, Hazlewood and Marshall (in [Rogers 2009]) demonstrate how this verbal and non-verbal communication can vary significantly, depending upon the configuration of entry-points. They show experimentally that by constraining the entry points to invite a clear division of labour, the interaction tends towards a command and control style, whereas a less constrained environment is perhaps suited to more open ended tasks requiring participation.

Rogers, Lim, Hazlewood and Marshall [Rogers 2009] along with Church, Hazlewood and Rogers [Church 2006] suggest that user contributions become more equitable as access to the surface is available to all and *'gate-keeping'* is reduced or eliminated, but other studies suggest that this intuitive benefit is not clear cut, and sharing a surface (and/or tangibles) can lead to control issues and affect levels of participation. For example, Pantidi, Rogers and Robinson (in [Pantidi 2009]) demonstrate using breakout sessions from meetings that in large groups, a pattern of behaviour emerges where a facilitator takes control. Also, Rogers, Hazlewood and Blevis (in [Rogers 2004]) demonstrated that turn-taking may be a natural pattern when interacting, as users, being polite, effectively self-govern the level of participation. And finally, Son do-Lenh and Kaplan's results [Do-Lehn 2009a] showed that by allowing multiple interactions, participants in a user study concentrated on their own efforts in favour of discussion with partners when compared with using a single mouse/keyboard, resulting in *diminished* learning outcomes.

An interesting side-effect on control behaviour when using tangibles was observed in [Marshall 2009]. In this paper it was shown that, with children, tangible items may be hidden or stolen in order to control access to the interface. [Marshall 2009] also references other studies which show similar behaviour in adults. Although this issue is not explored in the current research, it is perhaps reasonable to assume that in the context of Kolab, by allowing all users to improvise the tangibles, the opportunities for this behaviour style should diminish.

From the above, we can reasonably conclude that the number and configuration of access points may influence the way that the users interact and organise themselves. This is considered again when we discuss the interaction design of Kolab in chapter 3.

Before moving on to look at a range of TUI systems that define the state-of-the-art with respect to nomadic tangible interaction (section 2.5), we will conclude our presentation of tangible user interfaces with a look at a number of relevant studies into the use of abstract artefacts in collaboration (recall from Chapter 1 that one characteristic of an improvised tangible is that it may be abstract, meaning that its physical appearance may bear little or no resemblance to the underlying digital value).

2.4 Previous Studies

Many tangible user interfaces have been developed, but the presentation of such work is typically focussed on the system itself. Studies focusing on artefact improvisation in the context of tangible user interfaces for co-located collaboration are limited. Relevant work by Cheng, Liang and Chen [Cheng 2010] and Carvey, Gouldstone, Vedurumudi, Whiton and Ishii [Carvey 2006] investigates improvised objects as tangible controls and is covered in section 2.5. The work of Avrahami and Wobbrock [Avrahami 2011], which reports on the in-the-field issues experienced with a nomadic multi-application tangible system, has already been presented in Chapter 1, and is presented further in 2.5.1. In this section we present work by Edge and Blackwell which makes specific reference to collaboration in studies using abstract artefacts and we contrast it with the current research.

2.4.1 Abstract artefacts and collaboration

Edge and Blackwell have conducted a number of studies using abstract artefacts in collaborative contexts.

In [Edge 2006b] work was done specifically to investigate co-located collaboration using a system that offers configurable tangibles to collaboratively construct an argument. In this study, each token had an embedded RFID tag and a space to contain written user notes; using a GUI, students could associate images or other media to the token and physically write supporting notes on it. Each tangible represented a part of the argument and by placing tangibles in a rack students could walk through the argument while recalling the associated media. In this study they suggested that the trade-off between adaptability and expressiveness was not an issue.

Later work explored abstract artefact use in distributed teams [Edge 2009]. For this they used augmented (with hand-writing) poker-chip style type tokens to physically represent a user's tasks on the desktop. The proximity of the tokens to the computer indicated priority. The study was restricted to three people and they did not collaborate in the sense of working together on a shared task but the users did share the chips in a social exchange of tasks. The shared meaning of the chips was expressed by what was written on them.

In both studies the tangibles represented abstract concepts and although the tangibles were shared between users the abstract natures of the concepts and tangibles were overcome using handwriting. In contrast, the work presented in this current research examines the situation where the tangibles are used to represent digital values which may have a 'real world' equivalent.

2.5 Previous related systems

We now move on from the discussion about the benefits and limitations of tangible user interfaces to give some concrete examples of some existing relevant tangible user interfaces. The purpose of this section is to 'place' the Kolab prototype within the range of similar systems representing the state-of-the art.

As will be shown in Chapter 3 Kolab employs computer vision and hand gestures to realise techniques to allow users to improvised tangibles on a nomadic platform; in this section we review the state of the art in a number of areas related to this description of Kolab. Firstly we review current nomadic tangible systems including discussion on the use of gestures in these systems, we then extend the scope of the survey to examine the use of everyday objects in tangible user interfaces and we end this section with a table summarizing each of the systems described.

2.5.1 Nomadic Tangible Systems

The primary touch-points for Kolab are the systems 'Docklamp' [Do-Lehn 2009b],'Bonfire' [Kane 2009], 'PlayAnywhere' [Wilson 2005] and 'Portico' [Avrahami 2011]. These systems all look to extend the desktop beyond the host machine after Wellner's digital desk vision [Wellner 1991] by providing a tangible interface on a portable form factor. Reference to these systems is made throughout the current research, so a brief overview of each is presented.

Docklamp [Do-Lehn 2009b] is a portable bespoke device shaped like a large desk lamp. It uses a camera and projector in the 'lamp' and computer vision algorithms to detect fingertips and to identify specific labels printed on paper sheets. Some sheets are pre-printed with tools and keyboard keys which are touched by users to issue commands to the system and assign digital values to other blank tagged paper sheets. A blank tagged sheet is introduced and assigned value using the paper keyboard and the value is projected back onto the paper. The sheets and tools are used by teams to build up related concept maps.

Like Docklamp above, PlayAnywhere [Wilson 2005] is a bespoke device which sits on the desktop. Using a combination of projection and computer vision, the PlayAnywhere device uses labelled Perspex pucks to create a portable, tangible gaming environment for two or more users.

Similarly, Bonfire [Kane 2009] uses projection with computer vision, but instead uses a standard laptop computer rather than a specifically designed device as the basis for the system. With two projectors, two cameras and mirrors, 'Bonfire' uses projection to extend a laptop's work area onto a table. Using computer vision and object recognition techniques this extended work area can be populated with pre-learned objects to trigger predefined events on the system. For instance, a coffee cup on the table will trigger the display of daily coffee consumption onto the table; and the system will 'pause' any playing music when headphones are recognized as being on the table rather than being worn. The system can also recall a list of applications in use when an object was last placed on the table to support a kind of physical bookmark.

Finally, Portico [Avrahami 2011] is a recent development most closely related to Kolab. As with 'Bonfire'[Kane 2009] it uses projection and computer vision to extend the interface of a tablet PC onto the surrounding surface. By using predefined artefacts and a set of pre-learned objects, a multi-application TUI system has been developed and a small user study completed. The system supports multi-use for a number of games such as 'tic-tac-toe' and provides single user game controllers and objects 'off-screen', but critically, each application requires its own token set and the paper reported that the sets were mixed up by users and this stopped applications from operating correctly.

As mentioned above, the four systems presented here serve as the main comparison points for Kolab; all are portable and use computer vision in some way to provide a portable tangible interface. Significantly, where Kolab differs is in its use of improvised tangibles rather than relying upon fixed sets of tangibles, labels or pre-trained object recognisers. Another difference is in the use of hand gestures as part of the interaction; of these systems only Docklamp, like Kolab, has a gesture driven interface.

In their gesture-driven interfaces both Docklamp and Kolab track fingertips to enable pointing and tapping gestures to be detected *on* the surface (see chapter 3 for details of how Kolab achieves this). Unlike Docklamp, Kolab also uses the space *above* the table for gestures and is similar in this respect to Visual Touchpad [Malik 2004] and OmniTouch [Harrison 2011]. Visual Touchpad [Malik 2004] demonstrates how a two-handed alphabet of gestures can be detected above a surface to provide a 3D space for gestures to manipulate on screen data. Additionally, OmniTouch [Harrison 2011] demonstrates how portable touch surfaces can be developed using a commercial off the shelf depth sensor (the MS Kinect [Microsoft 2011]) and demonstrates the potential, in a single user system, of appropriating surfaces for use as a touch interface – this technique is also used in Kolab.

It is perhaps worth noting at this stage that although the use of gestures on the surface (e.g. [Do-Lehn 2009b] and the use of gestures above the surface (e.g. [Malik 2004]) is not novel, combining interactions *above* and *on* the surface is relatively new. As noted in previous sections, Hillages, Izadi, Wilson and Hodges [Hillages 2009] and Jota, Marquardt and Greenburg [Jota 2011] are looking to *'leverage the space above the surface'* [Hillages 2009 page 140] to increase the potential bandwidth of interaction in the *'continuous interaction space'* [Jota 2011]. Both systems (using back-projected displays rather than tangible interfaces) serve to demonstrate the potential of this interaction space and it is a space employed in the interaction design of Kolab (see Chapter 3).

2.5.2 The use of everyday and abstract objects

As one way around some of the problems outlined earlier, rather than design specific models such as in URP [Ullmer 2000], some researchers have looked towards using everyday objects within the interface to exploit their affordances. In this section we will survey a number of system that target the use of everyday objects and abstract tangibles for tangible interaction. What links them all - with the exception of 'Amphibian' [Carvey 2006] – is the limited sets of tangibles that may be supported. The systems presented below require that artefacts are augmented with electronics or labels, or limit the possible range of tangibles by using pre-trained object recognisers.

A number of tangible system have been developed that employ substantial electronics embedded into everyday objects or devices built to resemble everyday objects, for example systems such as 'I/O Brush'[Ryokai 2004],'Squid' [Stern 2008], 'MediaCups'[Beigl 2001], and 'MoSo'[Bakker 2011]. These systems illustrate how the affordances of everyday objects can be used in a user interface. The 'I/O Brush' [Ryokai 2004] is a brush-like device with sensors to detect colours textures to allow users to use any object as 'ink' which can be 'painted' onto a screen. In 'Sharing the Squid' [Stern 2008] a child's toy is used to support collaboration. The toy (a squid) is a control device linked to a nearby screen which displays the results of the teams' interactions and each tentacle contains a different controller. By collaborating, the team may achieve a goal using each of the different controllers. Stern, Kelliher and Burleson [Stern 2008] suggest that the playful nature of the toy helps in stimulating discussion and social bonds. 'MediaCup' [Beigl 2001] uses a cup with embodied electronics to detect both the state of the cup (e.g. full, empty) and its movement. This information allows the system to infer the cup's current use, such as *'drinking out of the cup'*. 'MoSo' [Bakker 2011] demonstrates how the affordances of objects can be used to teach the musical principles of pitch, volume and tempo to children.

Common to all of the above systems is the use of embedded electronics to provide the functionality of the device. Despite the possibilities this presents for increasing the functionality of the system, such a step fixes the choice of object very early on in the design stage and thus potentially *limits* the functionality of the device. It is worth noting that the use of embedded electronics does not *necessarily* limit a device as illustrated by work from Ullmer, Dever, Sankaran and Toole et al [Ullmer 2010] , Ullmer, Dell, Gill and Toole et al [Ullmer 2011] and Weiss and Remy [Weiss 2011]. Ullmer et al have begun to investigate 'core tangibles' in the form of *cartouches* [Ullmer 2010] and *casiers* [Ullmer 2011] to provide more generic application independent controls. Weiss and Remy [Weiss 2011] have investigated changing the physical properties of generic controls electronically to alter the haptic feedback. Possible techniques include changing magnetic resistance to give the impression to the user of a tangible changing weight. However these devices only offer the potential for general purpose tangible *controls* and do not address the representation of data objects.

By employing external sensors combined with labels or tags, a more ad-hoc object choice of everyday objects for data and controls is possible. A combination of labels and sensors is used in systems such as 'Augmented Documents'[Want 1999], and 'iCon'[Cheng 2010]. [Want 1999] used

RFID tags to associate common artefacts with information such that they could be tied back to a computer system as a form of interaction e.g. presenting an augmented business card brought up a blank email with the details of the recipient completed from the card. A similar idea was used in 'Bonfire' [Kane 2009] to link a coffee cup with a display of coffee consumption. 'iCon'[Cheng 2010] uses computer vision and fiducial marker labels to allow objects to be introduced as desk-top controllers linked to pre-programmed macros such as zoom, copy and paste.

Similar to 'iCon' [Cheng 2010], 'Amphibian'[Carvey 2006] is an example of a tangible user interface that allows objects to act as improvised desktop controls but by contrast it does not require additional labelling to recognise everyday objects brought to the interface. 'Amphibian' [Carvey 2006] uses weight to recognise objects and initiate shortcut commands on a user's desktop computer. Any object may be introduced onto a set of USB weighing scales that are incorporated into the system. The user may then associate the object with some desired macro pre-programmed on to the user's desk-top computer. Having made this association, reintroducing the object into the scales triggers the macro.

2.5.3 Summary of related systems and work

The table below summarises the systems discussed in the previous sections.

System [ref]	Use of everyday objects?	Allow user selection of artefacts	Augmentation of artefacts	TUI or Touch	Technology (Vision,RFID, Projection, Embodied)	Gestures	Multi-user?
Kolab – This current thesis	Yes	Yes	No	TUI	Vision, projection later.	Yes. On and above surface.	Yes
Sharing The Squid[Stern 2008]	Yes	No	Yes (RFID)	TUI	Embodied system.	No	Yes

I/O Brush[Ryokai 2004]	Yes	No	Internal Electronics	TUI	Embodied.	No	No
Amphibian[Carvey 2006]	Yes	Yes	No	TUI	Weight	No	No
onObject[Chung 2010]	Yes	Yes	Yes. RFID.	TUI	RFID detection and connected hardware	Yes through connected accelerometer	No
iCon[Cheng 2010]	Yes	Yes	Fiducial Markers	TUI	Vision.	No	No
PSITTI[Holzmann 2010]	Yes	Yes	No	TUI	Pressure signature on a special tabletop	No	Unstated but probable
MediaCups [Beigl 2001]	Yes but embodied.	No	RFID	TUI	RFID and on-board hardware.	No	No
deform [Follmer 2011]	No	No	No	TUI	Markerless and augmentation free TUI.	No	No
TouchSound [Peng 2011]	Yes	Yes	Yes	N/A	Variety of wrist worn sensors to convert the object and movement in to sound	Yes. Hand movement is part of the 'mix'	No
MoSo [Bakker 2011]	Simple Musical instruments	No	Sensors and wireless	TUI	Electronics	No	No
Bonfire [Kane 2009]	Limited set recognised	No	No	Touch	Vision and Projection.	Yes. On surface.	No
PlayAnywhere [Wilson 2005]	No. Perspex pucks.	No	Fiducial Markers	TUI	Vision and Projection	Yes. On surface.	Yes (2 player games)

Portico[Avrahami 2011]	Limited set recognised or special markers needed (except tamagotchi type game)	Yes	Object Recognition and visual markers	TUI	Vision and Projection	No	Yes (2 player games)
Docklamp[Do-Lehn 2009b]	Paper only.	Yes	Fiducial Markers	TUI	Vision and Projection	Yes. On surface.	No.
FACT[Liao 2010]	Paper only.	Yes.	No.	??	Vision and IR Pen. Projector.	No	No.
Sketch-A-TUI[Weithoff 2012]	Low fidelity prototypes	No	Special ink	TUI	Capacitive Ink	No	N/A
Visual Touchpad [Malik 2004]	N/A	N/A	N/A	N/A	Vision	Yes, on and above surface	No
OmniTouch[Harrison 2011]	N/A	N/A	N/A	Touch	Vision and Projection. Uses Kinect RGBD.	No	No

Table 1- A summary of similar systems

2.6 Other Supporting Literature

In this final section we describe the usability questionnaire and grading scale employed in the formal user study to help evaluate the usability of Kolab.

2.6.1 Standard Usability Scale (SUS)

The standard usability scale [Brooke 1996] is a set of 10 questions with answers entered on a 5-point Likert scale; odd numbered questions are phrased positively and even numbered questions are phrased negatively (see appendix D for a completed survey, this shows the full text of each question). The objective of the scale is to provide a quantitative measure for a user's experience of computer system usability.

Participants are asked to complete the survey after using a system. Participants respond to each of the 10 questions in the questionnaire by providing a score on a Likert scale in the range 1-5. With some exceptions discussed below, scores for individual question responses are meaningless. To get an overall usability rating from a completed questionnaire the responses must be converted into a 'final score' in the range 0-100.

The responses from a questionnaire are converted into a final score by first, adjusting each Likert response (in the range 1-5) to the range 0 to 4, then summing all 10 adjusted responses and finally multiplying the summed total by 2.5 to get a final score in the range 0-100. Recall that the odd numbered questions (1,3,5,7,9) are phrased positively. For these questions the individual Likert responses are adjusted to the range 0-4 by taking the response and subtracting 1. The even numbered questions (2,4,6,8,10) are phrased negatively and the scores for each of these questions are corrected to the range 0 to 4 by subtracting the response score from 5.

This final score is a single number representing a "composite measure of the overall usability of the system being studied" [Brooke 1996 page 5]. Consequently each returned questionnaire can be converted in to a score and the overall score for a system calculated as the average of all scores. Further work by Suaro [Sauro 2012] reports that a SUS score above a 68 would be considered above average and anything below 68 is below average.

As mentioned above individual question responses are meaningless however later work by Lewis and Sauro [Lewis 2009] shows that a subset of questions (Numbers 4 and 10) provides a measure of 'learnability'. 'Learnability' is the ease of which users feel they managed to learn a system.

3 The Kolab System

In this chapter we describe the Kolab system which was developed as part of the current research to provide a platform from which to explore the research question set out in Chapter 1

For the reader's convenience, we will briefly recap the principal background issues that set the context for the research question. As explored in detail in the previous chapter, tangible user interfaces generally use the physicality of artefacts and spatial multiplexing to realise user interfaces. Reasonable arguments suggest (see section 2.1) that such features broadly encourage learning and invite participation. As discussed in section 2.3, there has been a tendency in tangible user interfaces towards fixed form or iconic tangibles. This gives rise to the issue of flexibility over the form of the tangibles as designs are fixed early on in the TUI design lifecycle and TUI systems are developed to recognise and interact with limited object sets. More specifically, this reliance on *'explicit physical form'* may present specific problems for nomadic tangible devices that support multiple applications, since the need to transport multiple token sets tends to reduce maintainability and portability by increasing the overall bulkiness of the system.

This current research posits that one way to overcome the problems of artefact flexibility and overall system bulkiness is by developing a nomadic system that does not require specific sets of tangibles but which instead allows users to appropriate artefacts from the surrounding environment. In order to realise such a system, an interaction design is required to support the ad-hoc association of improvised tangibles with an underlying digital value or function (the *dynamic binding* of digital value to physical object). It is this type of interaction design, as implemented in Kolab, which is described in this chapter.

After describing the overall development methodology (section 3.1) the Kolab system is described in sections 3.2, 3.3 and 3.4. The hardware choices had a major influence on the interaction design so we begin our description of Kolab with an overview of its physical construction (section 3.2). In section 3.3 we recap the characteristic features of a tangible user interface and explain how they are realised in Kolab This is followed by a detailed description of how the interaction design was realised (section 3.4), including how the dynamic binding of digital data to physical objects is achieved. Having discussed the design of Kolab we briefly describe aspects of the software implementation that impact or constrain the system. A detailed description of the software implementation can be found in appendix H

We move on from the description of the Kolab system to describe the proof of concept application that was used in the formal in-the-field user study described in Chapter 5.

The chapter closes with a description of Kolab in terms of the descriptive frameworks outlined in section 2.2.

3.1 Development Methodology

Kolab was developed as a rapid prototype. As described in section 1.5 a functional, high-fidelity prototype was required for this current research. Prior to conducting the formal user study (see chapter 5) the Kolab system was developed over a number of iterations.

Early iterations of Kolab were tested by four users over a number of informal sessions at the researcher's home. These users did not participate in the final study. Early testing sessions concentrated on debugging in order to get the system working, later sessions concentrated on refining the interaction design. The prototype testing sessions used white paper index cards for tangibles.

As a result of the prototype iterations the final prototype physical setup and interaction design for the user study was developed. These are discussed next.

3.2 Physical Setup

The vision for Kolab is of a nomadic tangible user interface, this means it must be lightweight and easy to set up. To achieve this and in common with similar systems such as 'Portico' [Avrahami 2011], 'Bonfire'[Kane 2009],'Docklamp' [Do-Lehn 2009b] and 'Visual Touchpad'[Malik 2004] (see section 2.5) Kolab uses computer vision as its sensing technology because cameras are generally small and portable.

The introduction of the Microsoft Kinect [Microsoft 2011] as a low cost, lightweight, combined depth and vision sensor has created new options for low-cost vision based systems by providing an additional dimension (depth) to the 2-dimensional images captured from the colour camera. On this basis it was chosen as the sensor for Kolab. This choice of technology enabled the use of gestures both on and above the table to be incorporated into the Kolab interaction design, as described later.

As a result of the selection of the Kinect sensor, the Kolab system requires only a single sensor unit. This sensor unit is mounted on a tripod pointing down at the chosen surface and a notebook computer running the Kolab software. By using an off-the-shelf photography tripod, the system is easy to set up in a variety of locations and is not limited to rooms with pre-installed ceiling mounts. Refer to figure 1 (Chapter 1) for the prototype Kolab setup.

The only additional hardware to the sensor is a standard computer monitor. This is used as the main output device in preference to the notebook's screen. By using an external display Kolab is employing 'distant embodiment' [Fishkin 2004] (see also section 2.2). This means that the resultant output of the system is displayed remotely from the tangible input and can be considered as a 'worst case' for this aspect of a tangible system. Recall that a goal of this research is to examine the use of improvised tangibles with poor representational significance (see chapter 1). By employing 'distant embodiment' the tangibles used in the Kolab set-up will have no additional labelling or be enhanced in any way on the surface by the system (e.g. by using projected images or machine/human readable labels). This ensures that the poor representational significance of the tangibles is preserved as far as possible. Ad-hoc labelling by users (e.g. by writing, drawing or other marks) may occur if users so choose as this can be considered to be part of any improvisation.

3.3 Interaction Design and TUI characteristics.

Section 3.4 gives a detailed account of how the Kolab interaction design was realised. By way of a summary of the interaction design we will first review the interaction design in the context of the main characteristics of TUI. To recap from section 2.1, the main characteristics of a TUI are physical objects bound to digital representations; direct manipulation of the digital data; and real-time feedback; this section briefly summarises how Kolab provides these features.

Physical Objects

Physical objects in Kolab are bound to digital values by using a combination of gestures and tangible controls to navigate a list of digital values displayed on a nearby monitor. Tangibles to represent data and controls may be improvised from the surrounding environment and introduced on to the surface by users.

Importantly each user may associate digital values to physical objects independently of other users' actions; this preserves multiple access points into the Kolab system if required (see discussion in section 2.3.2 regarding the implications of multiple access points).

Direct Manipulation

Once a physical object has been bound to a digital representation, the users may directly manipulate the digital representation by interacting with the object. As already described physical 'control' objects can be used to make and mark selections from a list of digital values displayed on a nearby monitor. The interaction design of Kolab relies heavily upon spatial constraints [Ullmer 2005] that delimit the surface into specific areas or zones which change the function of an object and so change the effect of any direct manipulation. For instance, a physical object can be placed on the surface in a special control area and used as a slider control on the surface. A second control area is used to allow objects with the functionality of working buttons to be created. Whereas the slider control is manipulated by moving it across the surface the button style control is stationary. The button control is manipulated by a user pressing the object. This pressing action by the user triggers an underlying system action.

Each item on the surface is tracked and so the location of each object can be used expressively in applications where the arrangement of objects on the surface is significant. This type of application is referred to as a *'spatial application'* and such applications are typically implemented using iconic models or tokens [Ullmer 2000].

Real-time feedback

As mentioned above, real-time feedback is provided in the 'distant embodiment' style by a monitor at one end of the table. This monitor displays an image which shows the application-specific lists of digital values that users may associate to physical objects, as well as the current 'state' of the surface and any application specific feedback. The state of the surface is shown as a real-time image of the tabletop; on this image icons are super-imposed on the tangibles to communicate the associated values to all users. The extents of the spatial constraints described above are also shown by blue and red lines. This overall image is referred to in the following sections as the 'feedback-screen' or 'feedback-image' and examples can be seen in figures 2 and 6.

3.4 Interaction Design

A system based on improvised tangibles presents a number of unusual design challenges to be overcome. These design challenges are outlined below, in preparation for later detailed sections.

A fundamental property of improvised tangibles is that they do not come with any pre-assigned association to any particular digital representation. Consequently, an interaction design to support dynamic binding is required. This design must allow for each user to present artefacts and easily assign them meaning. Crucially, in the case of a sharable interface, this must be achievable in such a way that the activities of other users are not inhibited. This precludes the use of an 'offline programming mode'. In this context an 'offline programming mode' is where the system allows improvised tangibles to be bound to digital values but prevents other activities within the interface. Systems such as 'Amphibian' [Carvey 2006] and 'iCon' [Cheng 2010] employ this technique. Both of these systems use improvised tangibles but employ an 'offline programming' mode to allow users to bind digital data (in these cases macros) to physical items. Whilst in this mode users cannot manipulate the tangibles to invoke the associated system functions. These two systems are single-user systems and so this method of binding physical objects to digital operations is not necessarily an issue. This is in contrast to Kolab which is designed to support multiple users; as such this method is not suitable for binding physical objects to digital.

The overall interaction design was driven almost exclusively by a single consideration - how to represent the available range of digital values an artefact could take. Once this design decision was taken, the interaction design was decomposed into a set of mechanisms to allow multiple users to carry out any of the following activities in parallel with each other:

- navigate the range of digital values available,
- bind a chosen value to a specific physical artefact, and
- display the chosen binding of digital value to physical artefact back to all users.

The relevant mechanisms are described in the following sections.

Representing possible digital values

Kolab supports the appropriation of objects to act as tangibles; when first introduced onto the surface, these objects initially have no associated digital value or function within Kolab.

An initial design issue faced was to decide how Kolab could represent the possible digital values that an artefact can take and make this accessible to users in such a way that a specific digital value can be selected prior to being bound to a physical object. A decision was taken for Kolab to represent the range of values an improvised tangible can take as a list of discrete values which users can navigate in some way to select a single value from the list. The contents of the list are application specific and the list is displayed on the feedback screen (on the left and right hand edges of the schematic in Figure 2 and the screen shot in Figure 6).

Initial designs displayed the list in a 'carousel' style, showing one item at a time requiring users to navigate forwards and backwards to see the next or previous item in the list; initial trials during the prototyping stages suggested displaying the whole list was preferable and so the carousel style was replaced.

Another factor in the design of this aspect of Kolab was the number of lists that are available as this contributes to the number of access points into the system. One option was to limit it to a single list creating a single access point for which users may take turns to use. This would appear to have little advantage over an offline programming mode (discussed earlier in section 3.3) as it would force users to wait in order to introduce or re-bind objects limiting the interaction. For Kolab, a decision was made to have multiple access points to reduce the potential for gate-keeping behaviour (see section 2.3.2 for a general discussion of the impact of multiple access points). By allowing parallel use of the system through multiple access points the Kolab design does not impose any particular regime of sharing and users may alternatively opt for turn taking or 'gate keeping' behaviour may emerge if one user chooses simply not using the system. The multiple access points were manifested as two lists of digital values that may be independently navigated; in real terms this means that Kolab has two distinct access points that can be shared by multiple users. In anticipation of describing a user study involving pairs of users further descriptions will discuss 'two users' to maintain consistency between chapters however such references may be taken to also mean 'two groups of users'.

An external monitor is used for output purposes and as such a proportion of the interaction design was focussed on the 'feedback image' displayed on the screen. The feedback screen design at this stage looks like this:

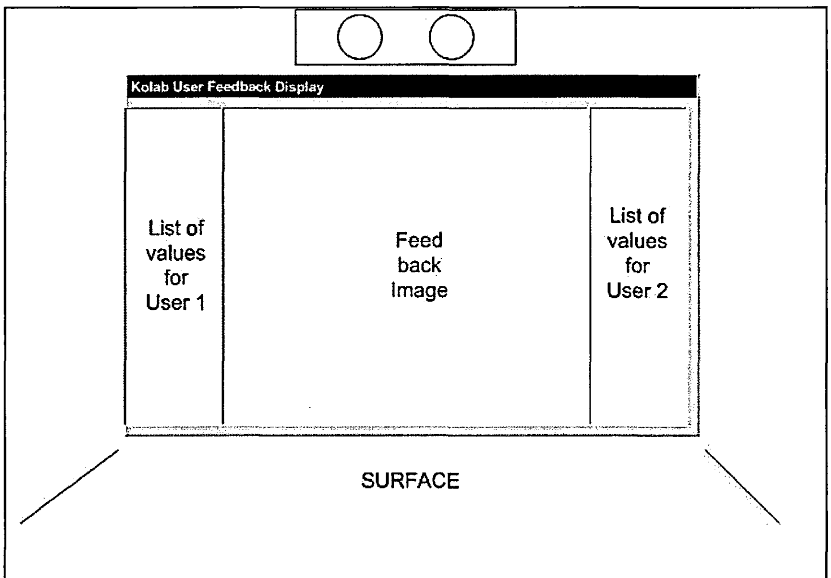


Figure 2 – Initial feedback screen layout

Having decided to support two access points and have two lists of values, each operated independently by users, the following features become necessary, each is discussed in its own section as shown.

- A mechanism to differentiate between users, i.e. determine which list is being used and which object to associate a value with – see 'Identifying users' below.
- A mechanism to navigate a list and select a digital value in anticipation of binding it to a physical tangible – see 'Navigation' below.

- A mechanism to bind the digital value to a physical tangible – see 'Binding a physical object to a digital value' below.
- A mechanism to show the bindings to all users – see 'The feedback display design' below.

Identifying users

Informed by the *'token+constraint'* approach (see section 2.2) the surface is split in to two halves and the prototype limited to two users facing each other, see figure 3 below. By using image processing algorithms the side a user is on can be determined and as such actions on and above the surface can be attributed to one or other of the users. The detail of these algorithms is presented in Appendix H which describes the implementation of Kolab in detail.

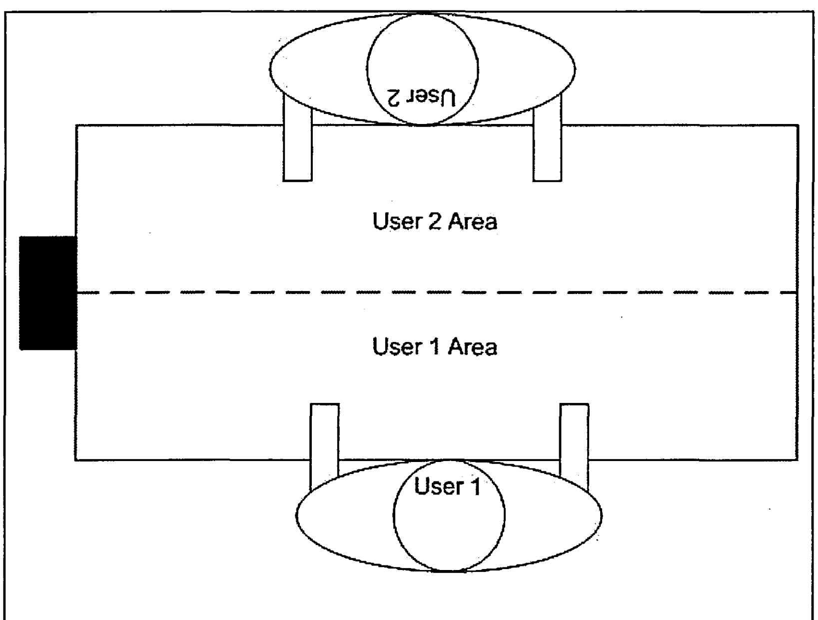


Figure 3 – User area spatial constraint

Navigation

Two alternative methods of navigation are designed into Kolab. One takes place *on* the surface and uses improvised tangibles as controls; the other takes place *above* the surface using a small vocabulary of gestures. Each of these strategies is discussed separately below.

Tangible Controls on the surface

Controls are a common feature of TUI , in a specific form (e.g. metaDesks phicons [Ullmer 1997]) or more general purpose forms such as 'casiers' [Ullmer 2011] and 'cartouches' [Ullmer 2010] or iCon's labelled objects [Cheng 2010].

In order to support controls in the context of Kolab a mechanism to introduce improvised tangibles as control objects is required.

The approach of *'token+constraint'* (see section 2.2) was again used to inform this area of system design and the main work area was 'split' into data and control sub-areas, see figure 4; This effectively placed spatial constraints upon tangibles placed on to the surface with the 'control' areas being similar to the idea of a rack of controls as used in the Tangible Query Interface [Ullmer 1998].

The *type* of control was also considered. The control's primary function within Kolab is to navigate a general list of unknown size and so must be capable of expressing a wide range of values. Work investigating *'cartouches'* [Ullmer 2010] and *'casiers'* [Ullmer 2011] indicate that dial style controls or block style controls have potential. To implement a dial control it must be possible to uniquely identify a reference point in order to detect rotation whereas a 'block' places no such restrictions on form and so a block or 'slider' control was selected as this offers the least restriction on tangible choice. Cheng et al [Cheng 2010] refer to this as a *'consecutive control'* and draw parallels with a volume control, such as found on a music mixing desk.

An artefact placed inside the control area can be tracked and its location determined inside the area. Within Kolab the control area is sub-divided into discrete steps, calculated by using the size of the list of values to be navigated; for example a list of 20 items requires the control area to have 20 discrete steps. Moving the slider object along the control area moves a pointer on the equivalent on-screen list to show which item is selected; this movement appeals to the spatial 'Up-Down' image-schema described in [Hurtienne 2007] (see section 2.2).

A 'button' or 'binary' [Cheng 2010] style control was also developed in a similar way to the slider control; a spatial constraint defined an area where artefacts function as binary controls and the depth sensing capabilities of Kolab are used to determine a 'click' gesture or operation on the artefact. This control style may be used to trigger simple system commands such as 'save'.

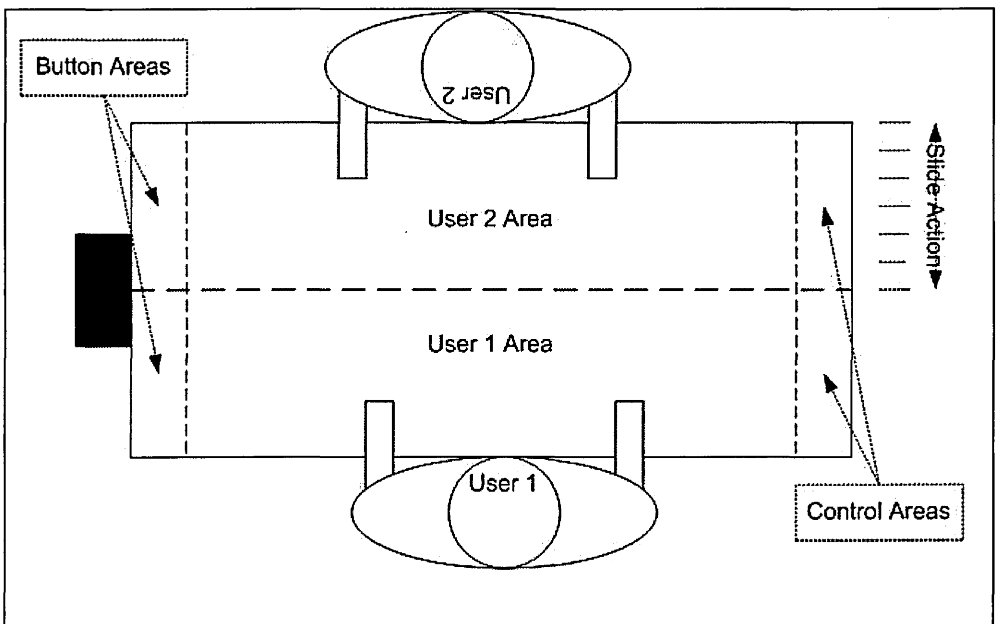


Figure 4 – Control area spatial constraints

Gestures above the surface

The use of a control area (see above) places constraints upon tangibles and requires users to be aware of at least two distinct areas of the surface(a 'data' area and a 'control' area), as well as potentially adding to the cognitive load it reduces the available space for performing the task at hand. As mentioned previously recent work such as [Malik 2004], [Jota 2011] and [Hillages 2009] demonstrate how the combination of touch 'on the table' and gestures 'above the table' are beginning to gain interest. By combining the two channels users are potentially offered greater modality for interaction and a potentially richer experience, referred to as *'spatial interaction'* in [Hornecker 2006] (see section 2.2).

Wobbrock, Morris and Wilson [Wobbrock 2009] suggest that the increasing use of touch based interfaces such as tablets and smart-phones may offer a more familiar user experience than designing a new vocabulary of poses specifically for Kolab. As such the Kolab interaction design looked to implement gestures that may be more immediately familiar to users. The 'line across for next/previous' gesture was selected as the basis for the gesture to navigate the list of values. Rather than being performed on the surface as for a touch surface, as described in [Wobbrock 2009], in Kolab the gesture is performed in the space *above* the surface - being a TUI we can assume that the surface may be cluttered with artefacts.

This *mimetic action* [Pavlovic 1997] is intended to imitate the moving of a carousel of images or the 'sweep' used on tablets and smart-phones, and can be achieved by tracking the finger-tip of a hand rather than requiring complex hand modelling or pose classification.

During testing it was found that attempting to mimic the slider control by making the gesture follow the same direction (an 'in-out' arm movement over the table) was very tiring and so a sweep across the table was used – a sweep towards the monitor is 'previous', sweep away is 'next'. Placing the control zone in the same direction was considered so that the physical slider also moved in the same direction across the table but this took up too much table space.

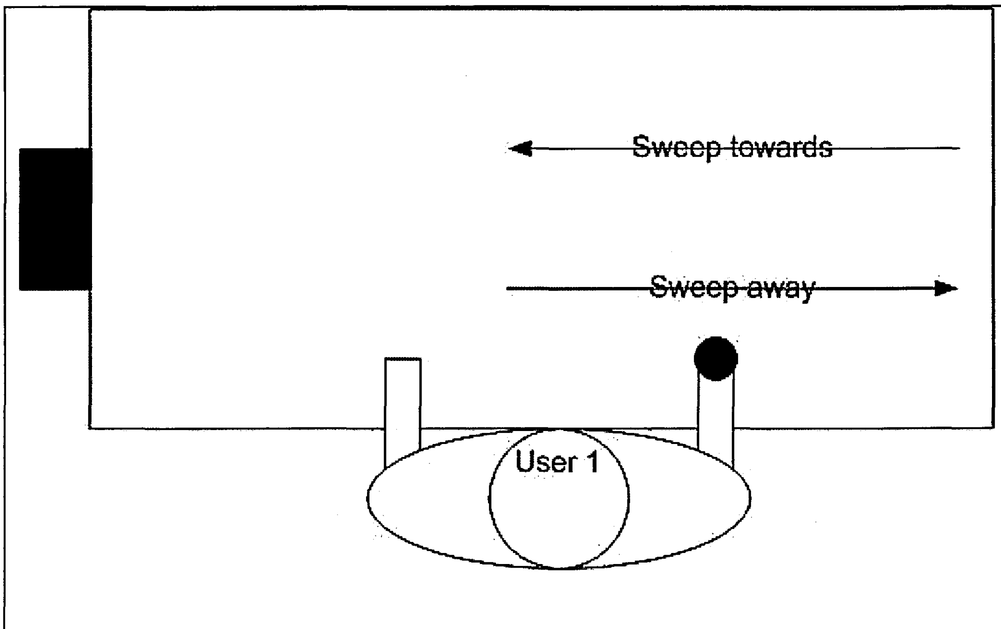


Figure 5 - Sweeping gesture over the table.

Binding a physical object to a digital value

The method of representing a list of values and interactions to navigate and select from it presented so far go some way to achieve the full range of interactions required to allow improvised tangibles to be used in the interface. Kolab must also provide a mechanism to associate the selected digital value with a specific physical artefact at run-time. This is the point where a specific physical object and a specific digital value finally become associated.

In order to support dynamic binding of improvised tangibles to digital values **Kolab** cannot make assumptions about the physical characteristics of the objects being selected and so this precludes imparting value by using physical markings such as pen markings and handwriting recognition or OCR (as used in [Wellner 1991] and [Klemmer 2000] for instance).

One possible solution is to employ an additional spatial constraint to define a 'programming area' as used in systems such as MediaBlocks [Ullmer 1998] which provides 'recording' slots; This would fit in with the design of the slider controls (discussed above) however the depth channel and gesture recognition scheme already considered for navigation offered opportunities to implement functionality similar to touch-tables such as [Wilson 2010] and [Dippon 2011]. As such a gesture driven approach was chosen to allow a user to select a specific artefact on the table and associate it with the currently selected value from the user's list by using hand gestures.

Again, [Wobbrock 2009] was used to inform the choice of gestures for this activity and the *deictic* [Pavlovic 1997] or pointing-style gesture 'Tap' was used to select a single artefact and 'Double Tap for open' was used to 'assign' or associate the current selected value in the list of values to the 'tapped' artefact.

<u>The feedback display design</u>

The interaction design relies heavily upon spatial constraints on the surface to create specific areas or zones; each user has a 'side' and controls are introduced and manipulated in specific regions. These zones are shown to users via the feedback-image (see figure 6 below, an enlarged version of which is in Appendix K) which is used to show the extent of the areas by the use of blue marker lines on the image.

The feedback image is also used to show the current data values of the physical objects on the surface by super-imposing iconic images onto a real time image of the surface; a control icon image is overlaid onto control artefacts, un-assigned artefacts show a question mark. The image also shows the lists of values (see above).

As a result of initial trials a coloured circle was introduced to indicate where Kolab had calculated the pointing finger-tip of users. The colour indicates which user it belongs to - red for one user and blue for the other.

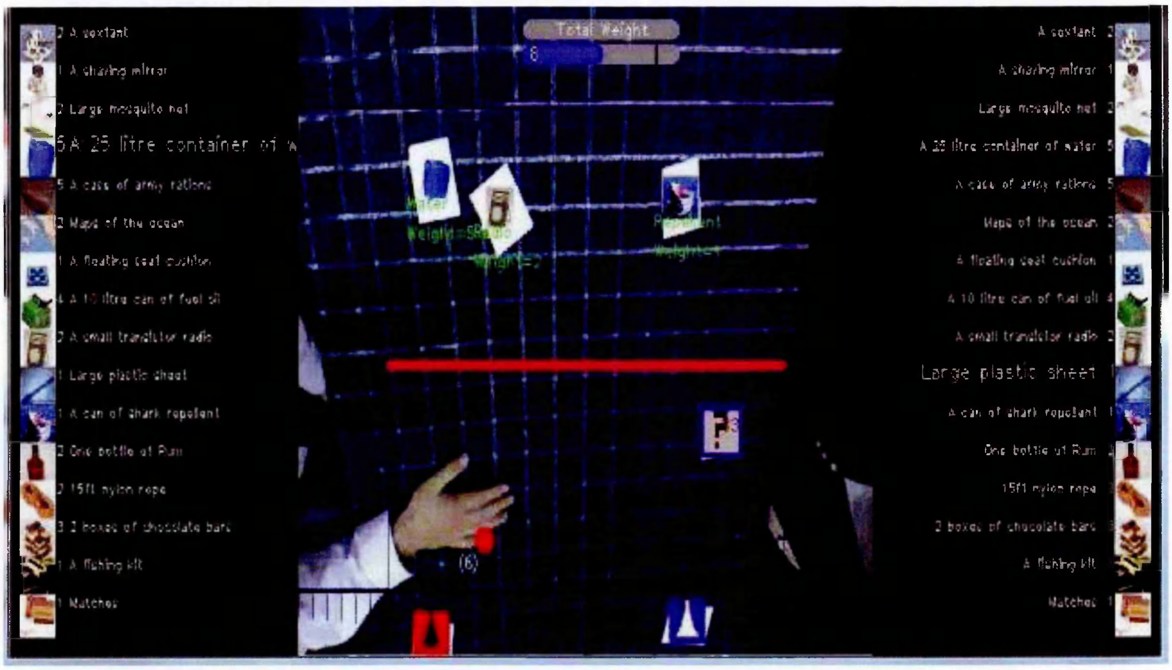


Figure **6** – Sample feedback screen from the user study. See Appendix K for a larger version.

To summarise the key operations in the interaction design; the surface is split into a data area and a control area. In order to import a new improvised tangible to represent an application specific digital value, the tangible is initially placed anywhere in the data area. A control artefact placed in the control area can be slid to highlight an item from the on-screen list. Figure 7 below summarises the interaction design. The new tangible item may be selected using a 'double tap' hand gesture. The selected tangible is then duly associated with the highlight on-screen digital value and the output display is annotated with both the name of the item it represents and a representative image. The sweeping gestures described earlier may be used to replace the slider controls to navigate the list of values.

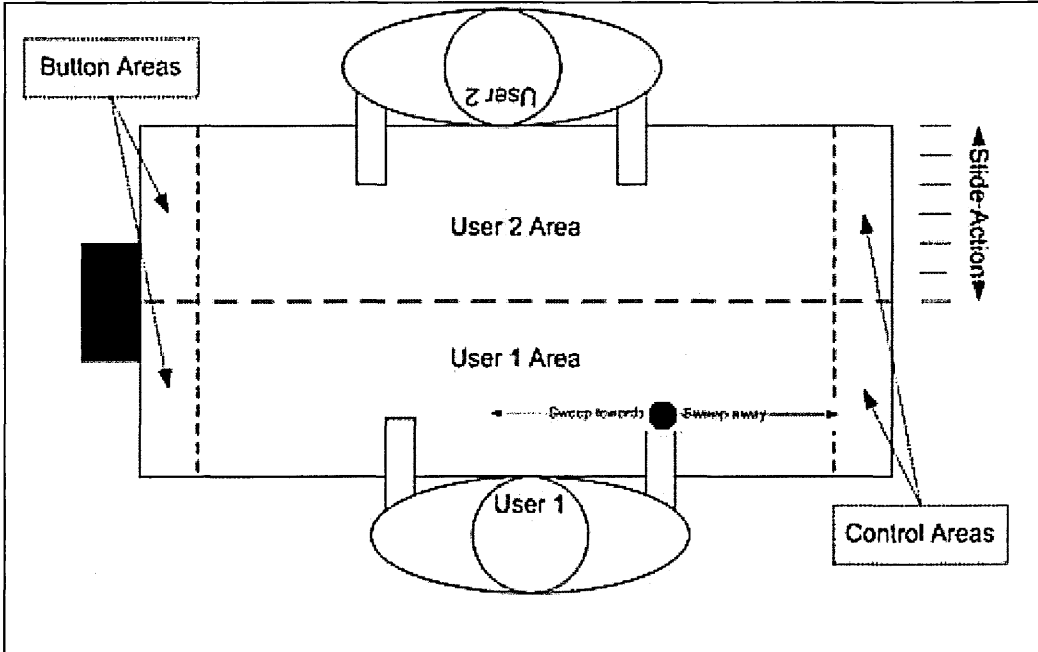


Figure 7 – Kolab interaction design schematic

3.5 Impact of Implementation and interaction design

By using minimal hardware, Kolab relies heavily on software to realise the required functionality described above. Software elements, just as much as hardware elements had an impact on the interaction design and placed some limitations on how the system could be used. Three aspects of the software as implemented had the most impact. These were a) the methods used to identify and track improvised tangibles on the table, b) the use of a depth sensor to provide touch-table functionality and c) the method of identifying the sweeping gestures. These aspects are discussed below and appendix H describes Kolab's construction and algorithms in more detail.

a) Kolab uses computer vision algorithms to track moving objects of interest to the system. These objects are twofold: the artefacts on the surface, and hands above the surface. In order to track improvised tangibles the algorithms cannot make too many assumptions about the physical characteristics of objects to be inferred from image data. For example features such as shape and colour cannot be relied upon as characteristics to differentiate items on the surface. More specifically, if for example users decide to use paper index cards as improvised tangibles then shape or colour alone cannot distinguish between two cards on the table. To alleviate this constraint a 'point based' tracking method was implemented. This method of tracking reduces the shape of an item to a single point by first extracting its outline or contour from an image and then calculating its centre of mass (using the method described in appendix I). Once reduced to a single point, each object is then tracked across image frames by matching the position of items in subsequent frames.

This method of reducing objects to a single point allows heterogeneous objects to be described by a common feature but does place a constraint on the positioning of objects on the surface. This is because by using contours as the main method of extracting information about an object Kolab cannot distinguish between two touching objects – these may be mistaken for a single large object.

As well as providing the basis for locating objects on and above the surface the contour is used to help filter out noise and changes in ambient light. This is achieved by imposing upper and lower thresholds on the area of a single contour and discarding as noise contours that are too small, while discarding contours that are too large as most likely indicating sudden changes in light. In practise this affects the size of objects that can be reliably recognised, and means that small items such as earrings and large items such as A4 sheets of paper cannot be used as improvised tangibles.

b) As described earlier, Kolab uses the Kinect sensor [Microsoft 2011] to provide a colour image and also a set of depth readings from its in-built depth sensor. The sensor takes two images at a time – a colour image and a corresponding depth reading or depth image. To use the depth images they must first be corrected in software such that the position of the depth measurements matches the corresponding locations on the colour. This is called rectification. The rectification process is imperfect and as such, two minor alterations to the interaction design were required to accommodate inaccuracies in matching locations in the colour image to corresponding depth readings. Briefly, these two alterations were as follows.

The depth image is used in Kolab to provide the touch-table functionality required for the 'tap' and 'double-tap' gestures described earlier. Due to small inaccuracies in calculating fingertip location, the first alteration was the addition of coloured dots on the feedback image as indicators to users of the calculated location of fingertips.

Secondly, Kolab must approximate which improvised tangible is being touched by allowing for a small radius around the calculated fingertip position when locating the nearest tangible to the fingertip.

c) The gesture recognition algorithms used to detect the sweeping gesture elements of the interaction design must be able to identify a sweeping gesture from other hand movements. In order to identify a sweeping gesture and extract out the meaningful 'nucleus' of the gesture [Pavlovic 1997], Kolab must be able to identify a clear start and end to the sweep, and the sweep itself needs to be very deliberate. This means that, in practice, the sweeping gestures need to be exaggerated otherwise it will rejected as an unintentional or non-sweeping action.

3.6 The Lost At Sea application

The description of Kolab so far has concentrated on the general functionality of Kolab. In order to provide a meaningful way to use the system a proof of concept application was developed. This application is an implementation of the team building task 'Lost at sea' [Wilderdom 2011] and provides an activity for pairs of users to collaborate in a task that requires an agreed solution. This type of task was chosen to represent a scenario similar to the spontaneous collaboration scenario presented in [Streitz 1999] where two users meet in a corridor and decide to take the opportunity to get together to address a shared issue.

The 'Lost at Sea' task is a problem solving exercise used to help individuals and teams to consider a solution to a hypothetical survival situation. The problem assumes participants are on a sinking ship with a single life-raft and no land visible. Players have to agree which items are to be taken into a life-raft, subject to a weight limit in order to maximise the chances of survival and rescue. Items can be useful on their own (e.g. food) or may only have limited use without other specific items (e.g. fuel and matches). Items may have short term benefits (e.g. a ration pack) or long term benefits (e.g. fishing kit to get an erratic but long term supply of food). Apparently valuable items may be useless (why take a reception-only radio when there is nothing to hear?). The final solution is scored to indicate how useful it would be in aiding survival using scoring criteria from [Knox 2011]. Table G.1 in appendix G shows a complete list of the 16 items available to participants and describes the scoring regime in detail.

Using Kolab, participants must construct an agreed solution to the survival problem using improvised tangibles. When each item is to be initially considered for rejection or inclusion, in order to allow the outcome of the decision to be visibly recorded, the item must be assigned to some suitable physical object. The location of the object on the surface can then be used to indicate whether it have been chosen to be 'in' or 'out' of a survival dinghy.

The interaction design described in section 3.4 was modified to support the Lost at Sea task. The surface was divided into three main regions – one 'in' and two 'out' (one per user). Items moved into the 'in' area are items chosen by the participants to be part of the solution. Figure 8 illustrates the configuration of the surface for the lost at sea task.

To allow users to track the solution, the application maintains a status bar indicating the current weight load of items chosen to be 'in' the dinghy, giving real-time feedback of the current solution state.

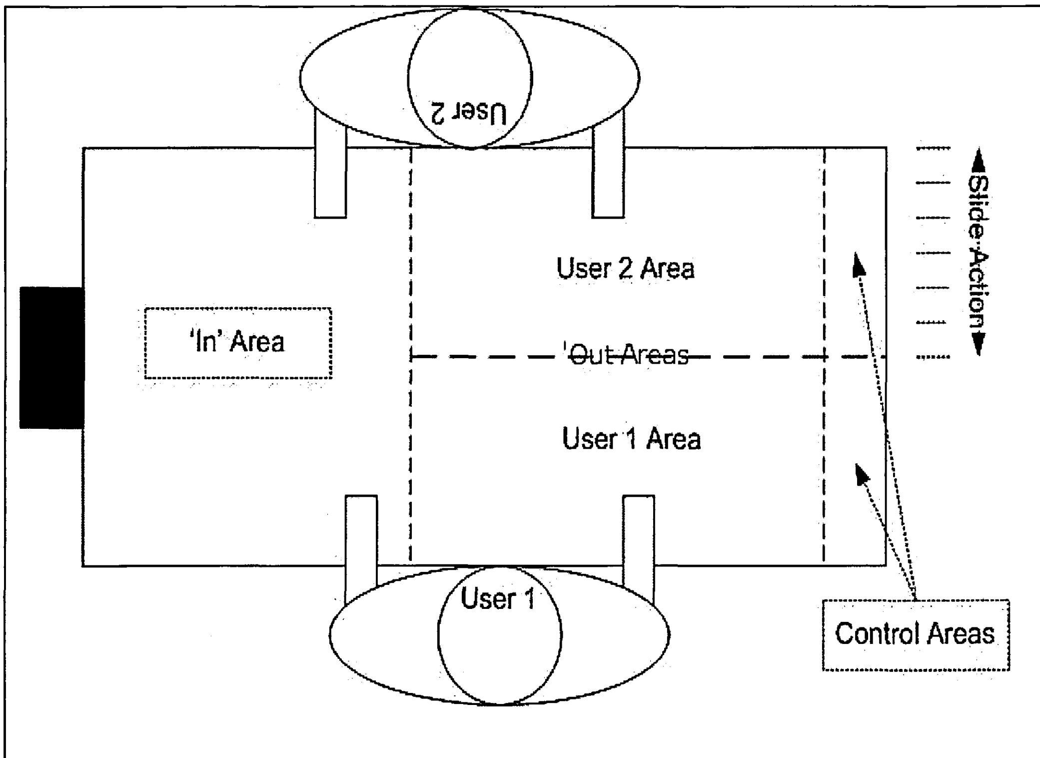


Figure 8 – Modified Kolab interaction design schematic

The 'in' and 'out' areas correspond to the idea of 'public' and 'private' territory ([Brignull 2004] and [Steimle 2010]) where 'private' spaces (labelled 'User 1 Area' and 'User 2 Area' in Figure 8) let users organise and construct small parts of solution before integrating with the whole solution in the 'public' space (the 'In area' above in figure 8). Once in the 'public' space a user's contribution becomes part of the overall solution.

The lost at sea task was originally implemented for use during the prototype sessions only. It provided a task that demonstrated the basic characteristics of a TUI (use of physical objects, direct manipulation of those objects, and real-time feedback of the results of the manipulation) and as such was a good test-bed for the prototype. During the prototype session it became obvious that the task was engaging and easy for users to pick up and so it was decided to use it for the user study.

As already discussed, as a TUI the lost-at-sea application does demonstrate the basic characteristics of this interface style but it is worth acknowledging that they are demonstrated in a very simple form; the direct manipulation is restricted to assigning value and moving tangibles between two spaces on the surface; also the underlying digital model is simply a single value tally of weight as items are moved into and out of the final solution. The task itself is a closed task, in that it has a fixed range of values that physical objects may take and these values are used to construct a scored solution.

The restricted use of spatial arrangement, the simplistic weight calculation and closed 'scored' nature of the task do highlight the limitations of the lost-at-sea application as a TUI implementation, limitations that will be expanded upon next by contrasting 'lost-at-sea' with a richer example of a TUI application, that of the planning application URP [Ullmer 2000]. Many example TUI applications could have been selected at this point but URP is revisited here for continuity because it was introduced in section 2.1 as an example of core TUI characteristics and is an example of a 'spatial application'[Ullmer 2000]. Here 'spatial application' is taken to mean as an application suited to the arrangement of pieces on a surface. In 'lost-at-sea' the spatial arrangement was restricted to its most simplistic form, that of an artefact being in or out of the final solution depending on where it is placed on the surface in one of two areas. By contrast in URP the *exact* location of an artefact has much more meaning, i.e. where it could be built, and so the exact position of an artefact in URP has much more significance that the position of an artefact in 'lost-at-sea'. Part of the underlying digital model for 'lost-at-sea' was a simple tally of weight values associated with the digital values associated with a tangible. This weight was included to add a constraint to the choices users could make when considering a solution. In more complex spatial applications such as URP the underlying digital model is far more complex and uses the inter-relationship of artefact positions to add meaning and richness within the application. In the case of URP the individual building positions had meaning (i.e. where they would be built) but also the overall position of the buildings in relation to each other were used by the application to calculate and display the overall layout's effect on wind-flow and lighting. This richness was missing from the lost-at-sea application. Finally we can consider the nature of the task itself. Lost-at-sea encouraged users to construct a solution that was scored to evaluate whether the solution was a 'good one' or not. This scoring limits the range of possible combinations of artefacts that are useful i.e. constitute a survival solution; URP is a more open-ended with no right or wrong answer but instead provides a platform to explore potential solutions.

Despite the simplistic implementation of the TUI interface style the task was chosen because it is relatively engaging and requires no specific job or task knowledge. This means it could be used by a wide variety of participants as part of a formal user study. Crucially for our purposes it offers a task with an easily understood and measurable end-goal viz. to agree a solution. Although not a realistic workplace activity in itself, the task does represent a simplified version of some typical workplace collaboration scenarios; for instance [Streitz 1999] puts forward workplace scenarios requiring informal spontaneous collaboration which may be short and specific to a single task and require on-demand facilities to support the collaboration.

3.7 Kolab and descriptive Frameworks

Having described the configuration and operation of Kolab in the preceding sections we close this chapter with a general description of Kolab presented in terms of the descriptive frameworks outlined in section 2.2.

Firstly we consider the descriptive frameworks which focus on the characteristics of the tangible system itself. In cognitive dimension terminology [Edge 2006a](section 2.2) Kolab supports low viscosity and low rigidity in its ability to allow any artefact to be used and associated dynamically with a corresponding digital value; also Kolab supports low rootedness in that the artefacts are freely movable on the surface. The system is predominantly a *data-centred view* [Hornecker 2006]

where data artefacts support noun based metaphors and the controls support verb based metaphors and feedback to users employs distant embodiment [Fishkin 2004].

Secondly we can consider the *Tangible Interaction* frameworks of Hornecker and Buur ([Hornecker 2006]) and Jacob, Girouard and Hirshfield ([Jacobs 2008]) to help characterise how users interact with Kolab and how the space around Kolab is used as part of the interaction.

Kolab supports the appropriation of surfaces and artefacts to create a tangible user interface which is part of the Spatial Interaction theme of Tangible Interaction [Hornecker 2006] where systems inhabit *the space*. By allowing dynamic binding of digital values to improvised tangibles Kolab provides for *configurable materials* and *tailored representations* which are components of the Embodied Facilitation theme [Hornecker 2006]. The 'deictic' tapping and 'mimetic' sweeping gestures used in Kolab support the concept of *performative action* [Hornecker 2006] and, from [Jacob 2008], draw upon the Body Awareness Skill (BAS) as part of the interaction design. The ability to spatially arrange objects on the surface appeals to the environmental awareness skills (EAS) and Naive Physics Skills (NP) described in [Jacob 2008]. Environmental awareness skills also come in to play when considering the use of improvised tangibles as part of Kolab's interface. Using this skill set users may potential employ objects that are not immediately to hand by looking beyond the immediate locality of the work surface to find suitable objects.

Finally we consider how Kolab uses constraints on the surface to create areas with specific meaning or functionality. These constraints rely upon the containment and spatial image-schema discussed by Hurtienne and Isreal [Hurtienne 2007] and illustrated further by Bakker, Antle and van den Hoven [Bakker 2011]. Bakker et al demonstrated that intuitive *'image schema'* [Hurtienne 2007] may be combined with the *'token+constraint'* approach [Ullmer 2005] to highlight the schemas that are being employed within the interface. They do on to suggest that these basic schemas (such as containment and spatial arrangement) are generally shared. Kolab exploits these schemas within a collaborative context to help offset the abstract nature of the spatial constraints.

4 User Study Objectives.

The previous two chapters have established the background required in order to move on and describe the user study that was undertaken to investigate the research question posed in chapter 1. To examine the research question this current research used a formal user study in which users are asked to complete a collaborative task using improvised tangibles.

The objectives of the user study were five-fold. Firstly, to test if users were able to complete tasks using tangibles appropriated from the environment; Secondly, to assess users' willingness and ability to improvise and appropriate tangibles from the surrounding environment; thirdly, to test the impact on usability of low 'representational significance' for nomadic tangible systems. Fourthly, to investigate what kinds of tangibles users selected, and the possible implications these choices might have on the design of more sophisticated recognition systems. Finally, to examine whether the overall interaction design of Kolab, including the use of improvised tangibles, in anyway discourages collaborative efforts.

To define these objectives in a more measurable way these objectives were translated into a number of detailed questions. These questions in turn were developed into associated evaluation criteria which describe how the study results were interpreted. For clarity we will refer to this new set of questions as *refined research questions* in order to differentiate from our overall research question. These refined research questions are listed in Table 2 below. The associated evaluation criteria are presented at the end of the next chapter once the overall study design has been explained because the methods of evaluation are dependent of certain specific aspects of the study design.

Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?	
1	Can users complete a collaborative task using improvised tangibles?
2	Are participants willing to use improvised tangibles?
3	Will users find such a system easy to use?
4	Will users find such a system easy to learn?
5	What sort of artefacts do users prefer to improvise with?
6	What sort of artefacts do users choose not to improvise with?
7	Will collaboration be encouraged?

Table 2- Refined Research Question

As mentioned earlier, during the design of the user study these questions were revisited to determine measurable evaluation criteria. The observations and methods employed to evaluate the refined questions are specific to the study design so consequently these methods of evaluation are presented in the following chapter which describes the design and conduct of the user study.

5 A formal 'in-the-field' user study using Kolab.

In this chapter we will present the formal in-the-field user study which was carried out to explore the refined research questions noted in the previous chapter.

An in-the-field (or in-situ) study was chosen over a laboratory study because this type of study helps explore how *'people appropriate technology outside of laboratory conditions in their intended setting'* [Rogers 2007 page 336]. This is relevant to nomadic tangible devices such as Kolab because a potential setting of these devices will be in relatively uncontrolled environments such as offices and homes.

A cross sectional, between subjects study in the field was developed in order to explore the refined research questions presented earlier in chapter 4. The study was also used as an opportunity to evaluate Kolab's interaction design in-the-field. The study was conducted between 4th July 2011 and 7th July 2011 in a single meeting room at the Swindon offices of English Heritage. It is worth noting that these offices are also the researcher's place of work and the study group was taken from the researcher's department.

In this chapter we describe how the study participants were chosen and organised, the task they were asked to perform and the data collection methods employed during the user study. The chapter ends with a definition of the evaluation methodologies for each of the refined research questions. The presentation of these evaluation methodologies has been deferred until the end of the chapter after the study has been described to ensure the background for the evaluation methodologies has been established.

5.1 Study Subjects

The sample for the study was drawn from the sample frame of the Information Management and Technology (IMT) team of English Heritage (a medium sized NGO) and as such users were of working age and computer literate although not necessarily 'technical' users. The study population was limited to volunteers and so in effect the sample was self selecting.

The participant pairs were selected and scheduled as follows. The whole department was emailed with a request to participate along with a calendar of available slots; this ensured that all department members were contacted as all department members have direct access to email via laptop, desk top or mobile devices. Volunteers were scheduled into session slots on a first-come-first-served basis into the slots they could make as responses to the invitation email came back. The study required pairs of participants working to together and so where a participant had no matching partner the timetable was adjusted to make up pairs according to availability. This email is in Appendix A. No inducement or reward was offered for participation.

Once selected, all participants were required to sign an informed consent form prior to taking part. This form communicated the fact that the research was independent of the organisation and that participation was entirely voluntary; it also clearly stated the purpose of the research and that video recordings were being made. The full form is in Appendix B and is substantially based on the version in [Rogers 2011].

The overall aim of the user-study was to show whether a TUI using weak representational significance is usable or not rather than provide a comparison of styles so no control group was required. The user study can therefore be described as a quasi-experiment [Coolican 2009] because the study is in-the-field and has no control group so as such is cannot described as a true experiment.

5.2 Study Task

In total 24 users participated. The users were organised into pairs and were asked to complete a collaborative task ('lost at sea', described in section 3.6) using the Kolab system. Grouping users in to pairs allowed the user-study to maximise the use of all volunteers. Each pair of users was asked to complete the user-study only once. To provide consistency between sessions each session took place in the same meeting room and each session was structured using the following standardised procedure (see appendix C for a detailed session timing notes):

- 10 minutes briefing and familiarisation session,
- 15 minutes completing the task using TUI controls,
- 15 minutes completing the task using free air gestures,
- 10 minutes open questions.

Figure 9 below shows the room setup for the user study.

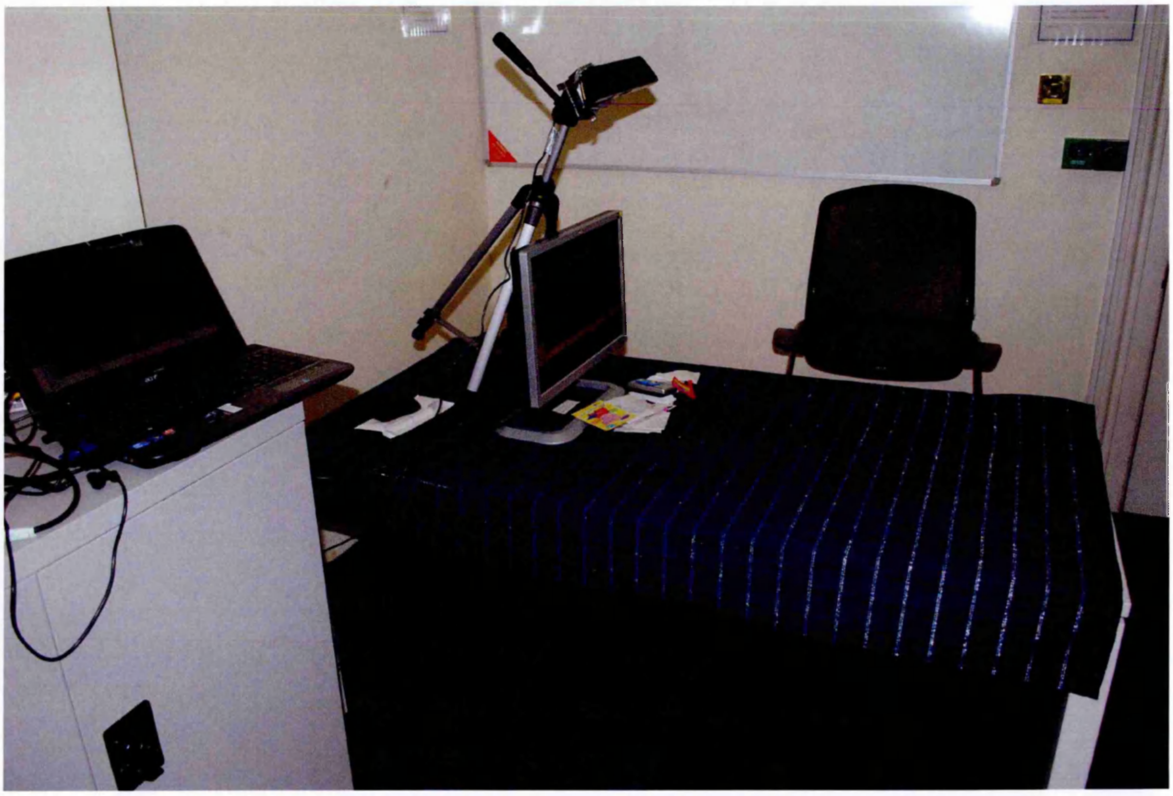


Figure 9 – User Study Setup

The workplace setting helped to afford the user-study ecological validity, but at the same time did place practical limits on factors such as the availability of people and the time they could spare away their from work. In order to overcome time constraints on each session and allow users to quickly begin using the system the user-study design incorporated an initial 'seeded' pool of objects available to use as tangibles. This pool was made up from objects found in the study area and is shown in figure 10 below. These items were added to by items brought in by participants. Any non-valuable, non-personal items left by participants were added to the pool for later sessions.

Figure 10 – Seeded items

Improvisation (defined as a user introducing a non-seeded object or modifying an existing object and attempting to use it during some part of the session) in the appropriation of tangibles was encouraged, but if such improvisation did not occur, or the objects appropriated did not work well, then participants could still engage with the system using seeded objects as tangibles.

5.3 Study Data Collection

In order to support the quantitative and qualitative evaluation of the system the following data sets were collected for each session:

- researcher notes recording success/failure of participants to complete the task,
- real-time video and audio footage of the room,
- real-time video of the surface,
- user Survey,
- post session open questions.

To capture the video, two cameras were used. The first was the table top camera that formed part of the 'Kolab' system itself, and which recorded all video input into the system. This arrangement allowed for detailed analysis of the table-top surface and the user interactions with the surface, as well as object usage. A second camera, which included audio, was positioned at the end of the surface to record a wider angle of the study area.

Each participant was asked to complete a user survey after they had completed the session. This was emailed to each participant as they left the study room. The usability survey was based on the 'Standard Usability Scale (SUS)' [Brooke 1996](see also 2.6.1). The SUS survey was used in its standard form with two additional questions asking the participant to rate (on a Likert scale) their own and their partner's level of contribution to the overall solution. An additional question was also included asking the user which interaction style of the two offered (tangible slider and free-air gestures) they preferred. Appendix D contains a sample of a completed questionnaire.

Upon completion of the study and analysis of the video streams it was noted that not enough information was available to itemize the pool of objects that were potentially available for use as improvised tangibles. The video field of view was not good enough to see all items brought in by hand, of course it could not view pocket or bag contents, and the questionnaire did not ask participants to enumerate these items.

A further survey was drawn up and sent out to the session participants asking them to enumerate the general types of articles they usually take with them to meetings. The survey email is in Appendix E. A sample response is in Appendix F.

5.4 Evaluation Methodologies

Chapter 4 presented seven refined research questions which decomposed the overall research question of this current research into a number of questions more readily examined in a user study. Before presenting the results of the user study in the next chapter we revisit these refined research questions and present how each one was to be evaluated.

Several questions (questions 1 through to 4, and question 7) described in chapter 4 could be evaluated quantitatively and so testable statements were defined for these questions prior to conducting the study these are described in section 5.4.1. For the remaining questions (questions 5 and 6) a qualitative evaluation was more appropriate, these are detailed in section 5.4.2.

5.4.1 Quantitative Evaluation

Recall that Chapter 1 posed the following research question:

Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?

As discussed in section 2.3.1 the core literature within the field of tangible user interfaces suggests that strong representational significance is a core characteristic of a TUI and that without it usability may be adversely affected. From this it seems reasonable to expect that a system such as Kolab (see chapter 3) which relies upon user selected objects that may have poor representational significance would suffer from impaired usability.

When considering what we mean by impaired usability in the context of the user study described in this chapter we may expect to observe the following outcomes :-

- The system will not be usable to the extent that a majority of users would fail to complete the given task. This may suggest that user simply cannot use a system based on improvised tangibles.

- The system will not be usable to the extent that a majority of users will not attempt use or to alter the objects available as tangible artefacts. This may suggest that users are not willing or cannot improvise tangibles.

Recall also from 2.6.1 that the SUS usability survey [Brooke 1996] provides a quantitative measure of 'usability'. Additionally the SUS also provides for a quantitative measure of 'learnability' which measures the ease of which users feel they managed to learn a system [Lewis 2009]. By using SUS we may measure a perception of usability and learnability from users and would expect the measures to be low if the system under test is not usable.

Recall that Kolab is a prototype platform intended to support collaborative work; and as such part of the user study was used to explore whether the Kolab prototype encouraged collaborative behaviour. To explore whether collaborative behaviour was encouraged during the user study the user survey included two additional questions to indicate each participant's view of their overall participation in the solution as well as that of their partner's. This choice was driven primarily by Marshall, Hornecker, Morris, Dalton and Rogers [Marshall 2008]. When considering sharable interfaces Marshall et al identify equitable participation as a desirable situation when looking at cooperative working. Equitable participation may come about due to many factors, for instance [Marshall 2008] demonstrates how the design of entry points to a system can influence levels of participation, so during this early stage of evaluating Kolab and the user interaction a simple indicator of participation levels was designed in to the study in order to identify whether collaboration is encouraged or not. The rationale being that if a participant views his/her level of input to a solution as the same as his/her partner then we can assume that the session was conducted in a collaborative and cooperative manner. Using this approach if equitable participation is encouraged then we would expect participants to report that their own contribution to the solution was equal to their partners.

From the expected observations above, measurable evaluation criteria can be defined for a number of the refined research questions. Table 3 below enumerates the quantitative evaluation criteria.

Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?		
Question from Chapter 4	Measurable Statement	Definitions
Can users complete a collaborative task using improvised tangibles?	*Using improvised tangibles a significant majority of sessions will fail to construct solutions to the given task within the time allowed*	Here we define an *unsuccessful session* as one in which the participants fail to agree a solution within the allotted time.
Are participants willing to use improvised tangibles?	*Only a minority of sessions (if any) will attempt to use items available outside of the object pool e.g. objects brought by in users or those away from the immediate are brought over onto the surface.*	In this particular study we define an *improvised tangible* as a non-seeded object introduced by a user or an existing object modified by a user. Consequently we use the term *improvisation* to refer to the

		specific event when a participant attempts to use such an improvised tangible
Will users find such a system easy to use?	*Due to the lack of representational significance and distant embodiment of system feedback users will find the system difficult to use and as such will return a low overall usability score.*	See section 2.6.1 for details of the Standard Usability Scale (SUS)
Will users find such a system easy to learn?	*Due to the lack of representational significance and distant embodiment of system feedback users will find the system difficult to learn. The average score for questions 4 and 10 (learn-ability) will be low.*	See section 2.6.1 for details of the Standard Usability Scale (SUS)
Will collaboration be encouraged?	*Marshall et al [*Marshall 2008*] identifies multiple access points as a means of encouraging collaboration. The extent to which collaboration is encouraged can be measured by considering individual levels*	Users will be asked to rate the level to which they felt they contributed to the solution and how much they felt their partner contributed. A Likert scale similar to those used in

	of participation as an indicator of collaborative behaviour. If collaboration is impacted then users may find that they could not contribute effectively to a solution and as such will feel that their contribution is low compared to their partners. *Users will rate their own contribution as low and their partners as high.*	the SUS will be used.

Table 3 – Quantitative Evaluation

5.4.2 Qualitative Evaluation

Additional to the quantitative measure described above by analysing the user study sessions we were able to evaluate the use and performance of Kolab, including the identification of the physical objects that participants chose to use as part of the interaction (Refined research question 5). This was achieved through analysing video recording of the sessions as well as asking participants to comment on their experiences in response to open questions at the end of the session. The qualitative data was used to further explore the user experience of using a system such as Kolab.

The refined research question number 6 (*What sort of artefacts do users choose not to improvise with?)* required an additional survey to be conducted, as was described earlier in section 5.3.

In this chapter we described the format and conduct of 12 user study sessions, the types of data that was collected in each and how the data collected related to evaluating the refined research questions. The following chapter presents relevant results from the user study.

6 Results

The preceding chapter described the design and conduct of a 24 participant user study conducted in-the–field at the offices of a medium sized non-government organisation. The study used the Kolab platform and the 'lost-at-sea' application (both described in chapter 3) to examine a set of refined research questions designed to explore the use of improvised tangibles when used in a collaborative context. These refined questions were detailed in chapter 4.

We now move on to presents the results from the user study. The results of the quantitative evaluation are presented first (in section 6.1). This section is followed by the qualitative evaluation results which includes the results of the additional survey described earlier in section 5.3. Section 6.3 is a summary of a number of points that emerged from the study regarding the interaction design of Kolab. The chapter concludes with a summary of the results.

6.1 Quantitative Evaluation

This section presents the user study results for the quantitative evaluation measurements presented in chapter 5. During the study there were 12 sessions and 24 participants. 21 of the 24 participants returned completed questionnaires.

6.1.1 Success Rate

100% of sessions achieved an agreed solution (not necessarily one in which participants 'survived') when using the system in at least one of the configurations.

In 12 sessions, two configurations per session, there were 24 attempts, of which 20 achieved a solution and 4 did not – all 4 were due to the gesture recognition scheme not working well enough for users to successfully come to a solution. Table 4 gives a full breakdown of the session results.

Session	Slider	Gestures
1	Solution	No Solution
2	Solution	Solution
3	Solution	Solution
4	Solution	No Solution
5	Solution	No Solution
6	Solution	Solution
7	Solution	No Solution
8	Solution	Solution
9	Solution	Solution
10	Solution	Solution
11	Solution	Solution
12	Solution	Solution
Agreed Solution	12	8
No Solution	0	4
Survived	10	7
Not Survived	2	1

Table 4 - Summary of success rates by session and navigation style.

6.1.2 Improvisation

In the 12 sessions, improvisation occurred in 9 sessions (75%). Improvisation is defined as a user introducing a non-seeded object or modifying an existing object and attempting to use it during some part of the session. During the sessions 13 of the 24 participants (54%) used non-seeded items or modified seeded items as tangibles during the course of the session either during familiarisation or task completion; this figure includes 2 participants who modified seeded items and 1 user who reused an item introduced by their partner.

Introduced items were Mobile phones (2 sessions tried these), Cuff link, Teaspoon, Paper animal, Origami cube, Pencils and Pens, Coffee Cup, Cigarette Packet and Childs Camera Toy. Modified seeded items were folded paper and Stacked Coffee Tops, used in 1 session each. It should be noted that this list includes attempts at improvisation made during the familiarisation phase of the sessions and items that were not subsequently used to construct a solution due to limitations in the recognition and tracking. See section 6.2.1for a detailed breakdown of items used and section 6.2.2 for a more detailed discussion about improvisation.

6.1.3 Usability and Learnability

From the 21 returned questionnaires the overall usability overall usability score of 65.5 was calculated, this calculation was performed in line with the scheme described in section 2.6.1.The overall score of 65.5 shows that the system was slightly below the mean usability score of 68 (see section 2.6.1). Table 5 below shows each participant's calculated usability score.

As described in section 2.6.1 individual question responses from the SUS are meaningless with the exception of a subset of questions which have been shown (in [Lewis 2009]) to provide a measure of 'learnability'. From the 21 responses these two questions (SUS4 and SUS10) returned an average (mode) score of 4 for SUS4 and 3 for SUS10. Both scores are from a possible range of 0-4 and so can be considered to be 'high' scores. Table 6 details the frequency of all responses to these two questions.

Respondent	SUS Score	Respondent	SUS Score
1	60	12	60
2	62.5	13	67.5
3	60	14	70
4	60	15	42.5
5	62.5	16	82.5
6	82.5	17	75
7	55	18	57.5
8	50	19	85
9	70	20	57.5
10	60	21	80
11	75		
		Average	65.5

Table 5 – Individual SUS scores from each participant.

Score	SUS4	SUS10
0	0	0
1	0	0
2	1	1
3	10	12
4	10	8

Table 6 – Frequency of SUS responses for questions 4 and 10. Most frequent responses are highlighted.

6.1.4 Contribution to the Overall Solution

As part of the questionnaire each participant was asked to rate their own and their partner's level of contribution to the overall solution. The average (mode) response of 3 (from a scale of 1-5) indicates that on average participants considered their contribution to the overall solution was equal to that of their partners.

Perceived Level Of Contribution						
	1	2	3	4	5	Mode
I contributed most to the overall solution (1-Strongly Disagree,5-Strongly Agree)	2	6	8	5	0	3
My partner contributed most to the overall solution (1-Strongly Disagree,5-Strongly Agree)	1	3	12	5	0	3

Table 7 – frequency of responses to questions 11 and 12. Most frequent responses highlighted.

6.2 Qualitative Evaluation

From data primarily collected by video analysis and from recording comments made by participants during sessions a qualitative analysis of the user study sessions is presented. As mentioned previously, an additional questionnaire was sent out by email to all 21 original respondents to indicate what items they would normally take into a meeting. There were 11 responses and the results of this are presented in section 6.2.2.

6.2.1 Analysis of artefact types used.

From table 8 we can see that a wide variety of items were used during the study sessions.

Summary of Artefact usage (by percentage of sessions using it) ranked by the percentage of sessions the item type was used in. Highlighted items had significant vision issues.					
	Seeded or Not?	%age of sessions item type used	%age of sessions item type chosen as very first item	%age sessions where item type left on surface at end	%sessions Item type used as sliders
Coffee Cup tops	S/NS	100.00%	41.67%	100.00%	58.33%
Tickets	S	91.67%	16.67%	66.67%	25.00%
Paper scraps (10cm x 7cm approx)	S	83.33%	41.67%	83.33%	58.33%
Sachet of gel drink	S	83.33%	16.67%	33.33%	16.67%
Corporate postcard	S	75.00%	8.33%	25.00%	16.67%
Cardboard Cup Holder	S	66.67%	16.67%	16.67%	33.33%
Tea Bags	S	58.33%	0.00%	50.00%	8.33%
Sugar Sachets	S	58.33%	8.33%	41.67%	33.33%
Pencils and Pens	NS	33.33%	0.00%	0.00%	0.00%
Napkins	S	25.00%	0.00%	25.00%	0.00%
Mobile phones	NS	16.67%	0.00%	0.00%	0.00%
Folded paper (modifying seeded items)	NS	16.67%	0.00%	16.67%	0.00%
Toy Brick	S	8.33%	0.00%	8.33%	0.00%
Jewellery (Cuff link)	NS	8.33%	0.00%	0.00%	0.00%
Teaspoon	NS	8.33%	0.00%	0.00%	0.00%
Paper animal	NS	8.33%	8.33%	0.00%	0.00%
Origami cube	NS	8.33%	0.00%	0.00%	0.00%
Coffee Cup	NS	8.33%	0.00%	0.00%	0.00%
Cigarettes	NS	8.33%	0.00%	8.33%	0.00%
Childs Camera Toy	NS	8.33%	8.33%	8.33%	8.33%
Stacked Coffee Tops (modifying seeded item)	NS	8.33%	0.00%	8.33%	0.00%
Bottles/Drink containers	NS	0.00%	0.00%	0.00%	0.00%
Notebook	NS	0.00%	0.00%	0.00%	0.00%
Spectacles (not worn)	NS	0.00%	0.00%	0.00%	0.00%

Table 8 - Analysis of artefacts by session.

Coffee cup tops, tickets and paper were the most popular medium for artefacts. Both coffee cup tops and paper were used extensively as slider controls as well as data items. Highly reflective and small items caused the most significant computer vision issues; highly reflective surfaces such as coffee cup glaze and cigarette packets created multiple tracking targets that 'jittered' significantly as the reflected light moved; small items such a cuff links and pens/pencils were rejected as 'noise' due to the object filtering thresholds employed (see section 3.5).

Generally artefacts that 'slid' well on the cloth surface were used in preference to objects that did not easy slide across the surface, especially when selecting control tangibles to act as a slider for example several attempts were made to use the tea-bags as slider controls (sessions 3 and 10) but the 'drag' on the cloth surface meant they were quickly replaced (by paper and a sugar sachet). Session 7 did successfully use the teabag as a slider.

When using the slider control we did see artefacts take on multiple roles within a session. Users typically used one item as a slider and introduced separate items for 'programming' as data. However, in some cases, for example in session 5, users took an object, used it as a slider to select a list item, and then moved the same object into the data area to be associated with the list item. In other words, in this session the same physical object was used successively as both data and control.

The size of the artefacts used created some issues as larger objects such as corporate postcards soon filled the work area, examples of which occurred in sessions 10 and 12; introducing these objects required the artefacts on the surface to be rearranged. In session 10 the larger postcards were replaced with smaller cardboard cup holders and plastic lids.

The behaviour described above from session 10 highlights an important feature of dynamic binding - the same digital values can be associated with different physical objects within the same interaction or session. Similarly, the same physical object can take on different digital values or function in the same session; this was demonstrated most clearly in session 5 where an artefact was chosen, used as a slider to select a digital value, and then the same artefact was moved in to the data area to take on that value. In this way several objects in this session acted as both control and data artefacts. In one case the artefacts took on no digital value at all and a user used the affordances of artefacts to provide a physical guide to the implied spatial constraints. The user in session 11 placed 2 artefacts (a ticket and a postcard) on the surface to provide a physical guide to the location of the control zone (see figure 11 below).

Figure 11 – Novel use of artefacts to mark out spatial constraints. This detail from a larger image shows how a user improvised two tangibles, a ticket and a postcard, to act as physical markers of the control area and to provide guides for the slider object (a toy camera).

6.2.2 Improvisation and additional questionnaire

Section 6.1.2 lists the items users attempted to improvise with. This same list is presented in tabular form in table 9 with additional data showing the items seen on the video footage that were brought in and not used. Table 9 shows that stationery such as pens and pencils as well as drinks containers were frequently brought in to the study room.

Improvised Items	Brought in and used	Brought in and not used	Brought in
Mobile phones	2	0	2
Cuff link	1	0	1
Teaspoon	1	0	1
Paper animal	1	0	1
Origami cube	1	0	1
Pencils and Pens	4	3	7
Coffee Cup	1	2	3
Cigarettes	1	0	1
Childs Camera Toy	1	0	1
Folded paper (modifying seeded items)	n/a – seeded	n/a	n/a
Stacked Coffee Tops (modifying seeded item)	n/a – seeded	n/a	n/a
Bottles/Drink containers	0	2	2
Notebook	0	1	1
Spectacles (not worn)	0	1	1

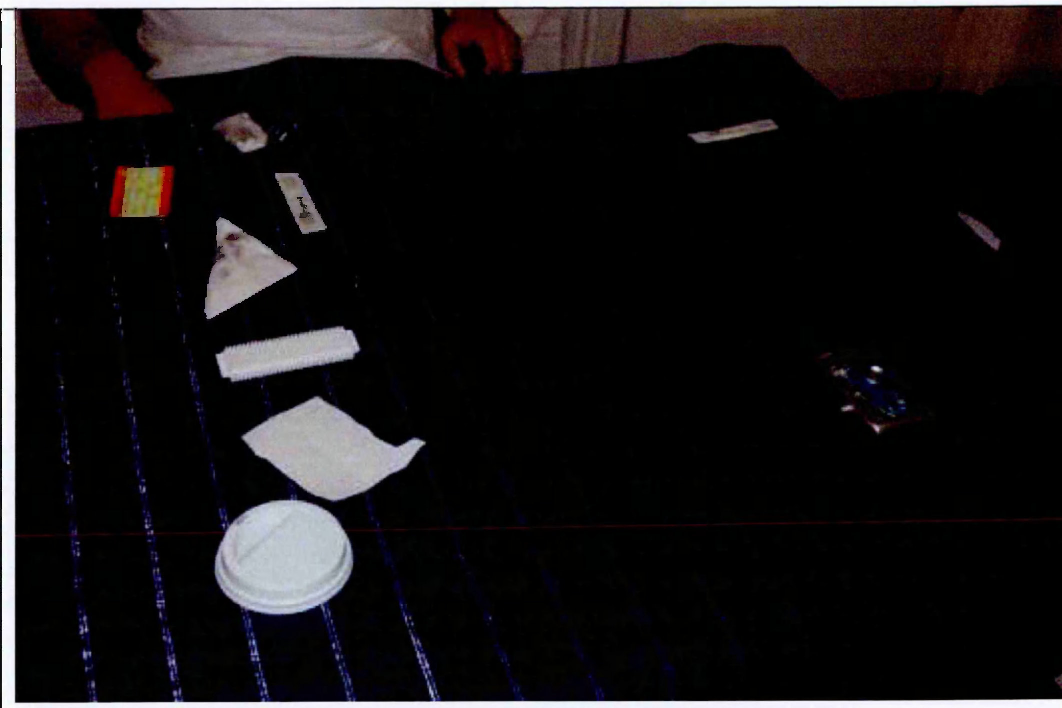
Table 9 – Breakdown of improvised objects and those that were seen to be brought in by users but not used.

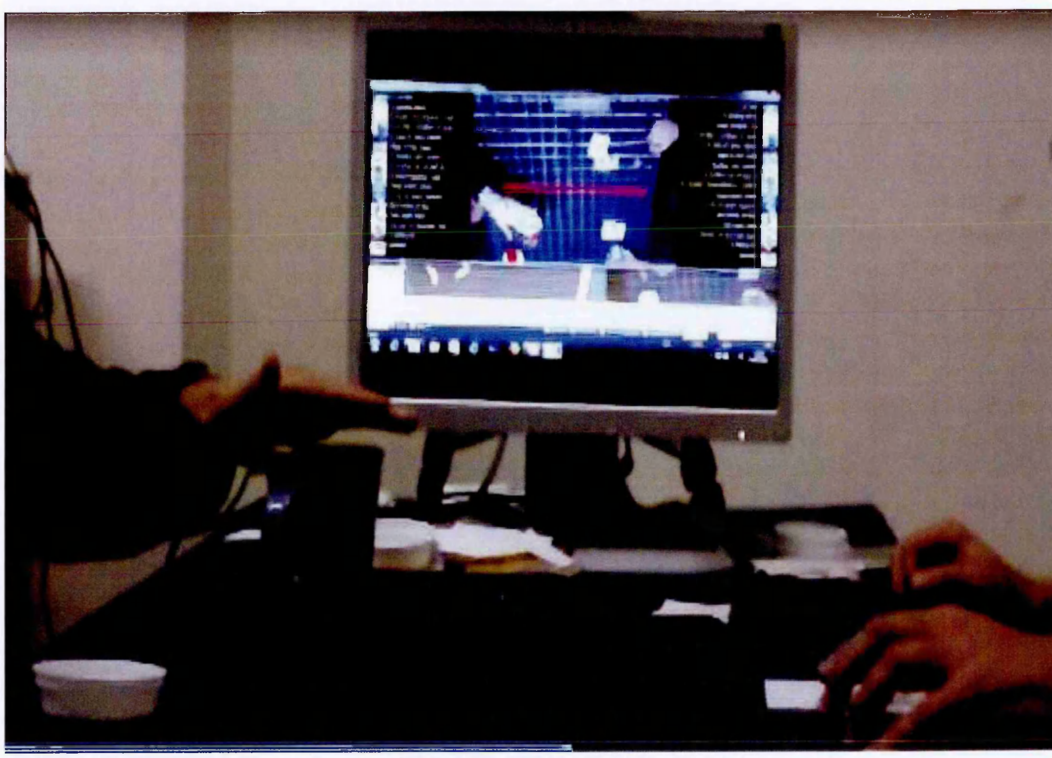
As a follow-up to the user study, a brief retrospective survey was conducted to discover what participants would normally carry with them in the office and would normally take into a meeting; mobile phones, pens, security passes and notebooks were common articles. The table 10 summarises the 11 responses to the additional survey.

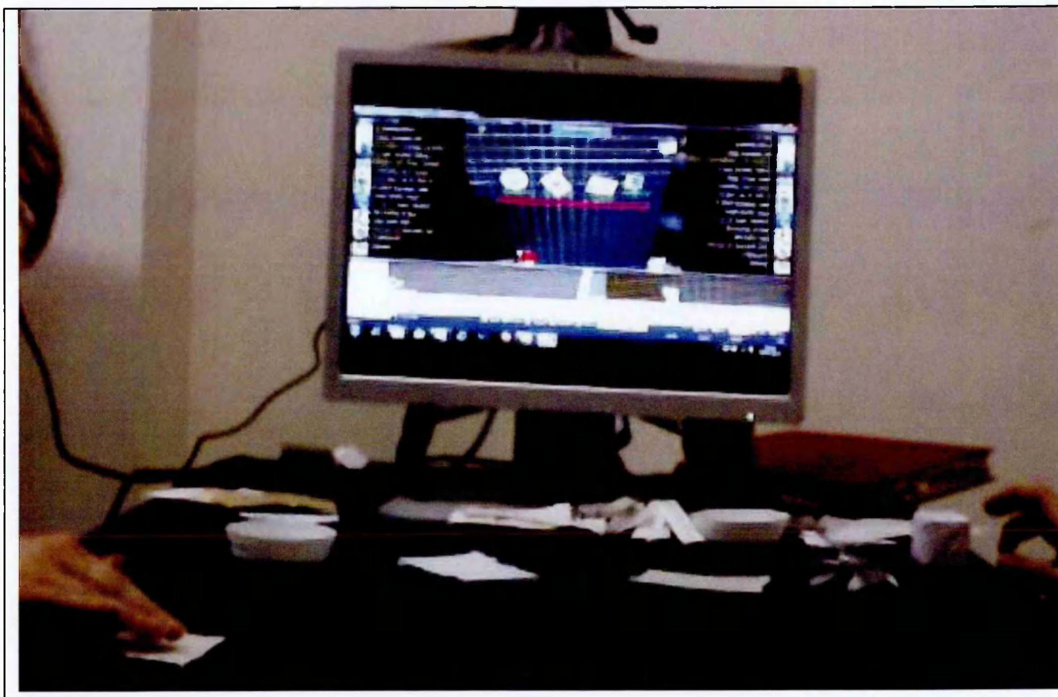
Items Carried		Total
Keys	63.64%	7
Security Pass	90.91%	10
Coins	63.64%	7
Notes	36.36%	4
Credit Cards	45.45%	5
Wallets/Purses	54.55%	6
Membership/Other cards	27.27%	3
Business Cards	18.18%	2
Smart Phone/Electronic organiser/Phone	81.82%	9
Receipts	9.09%	1
Pens/Pencils	90.91%	10
Notebook etc	90.91%	10
Coffee/tea cup	63.64%	7
Other Drink container	18.18%	2
Bag	9.09%	1
Other (please state)	27.27%	3
* Laptop (occasionally)		
*Origami		
Total Responses	11	

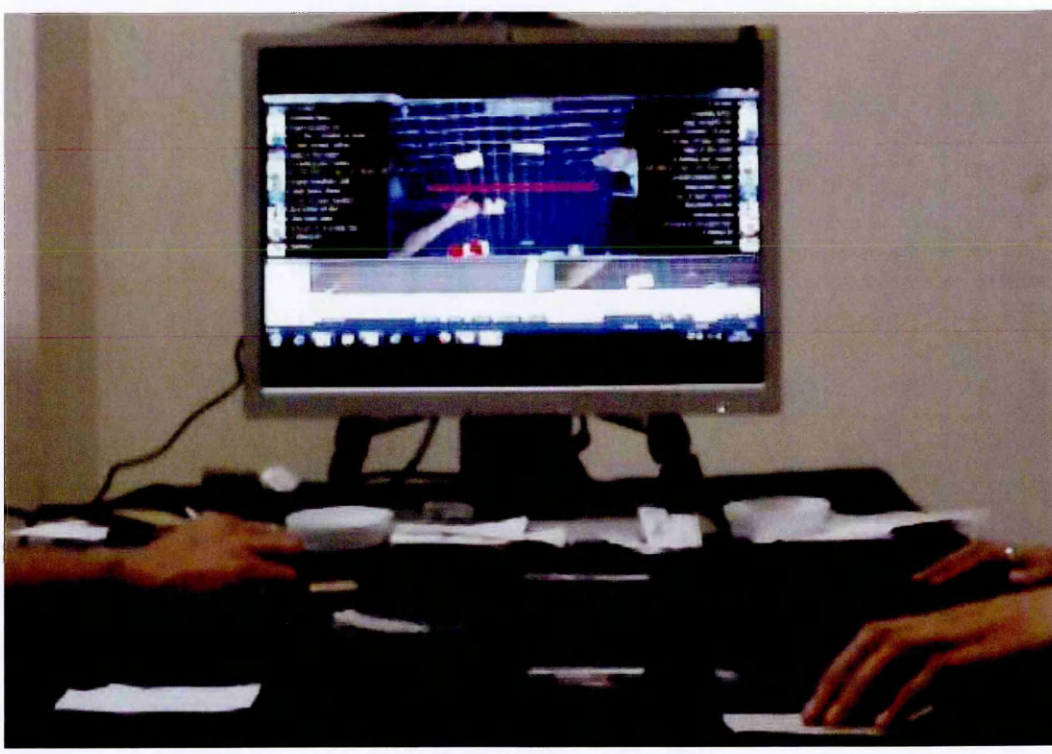
Table 10 – Responses from additional offline user survey.

The following sequence of images in figure 12 illustrate some of the items used during the sessions including train tickets, a ceramic coffee mug, plastic coffee cup tops, toys, sugar, tea bag, pen, mobile phone, cigarettes, origami, napkin and paper.









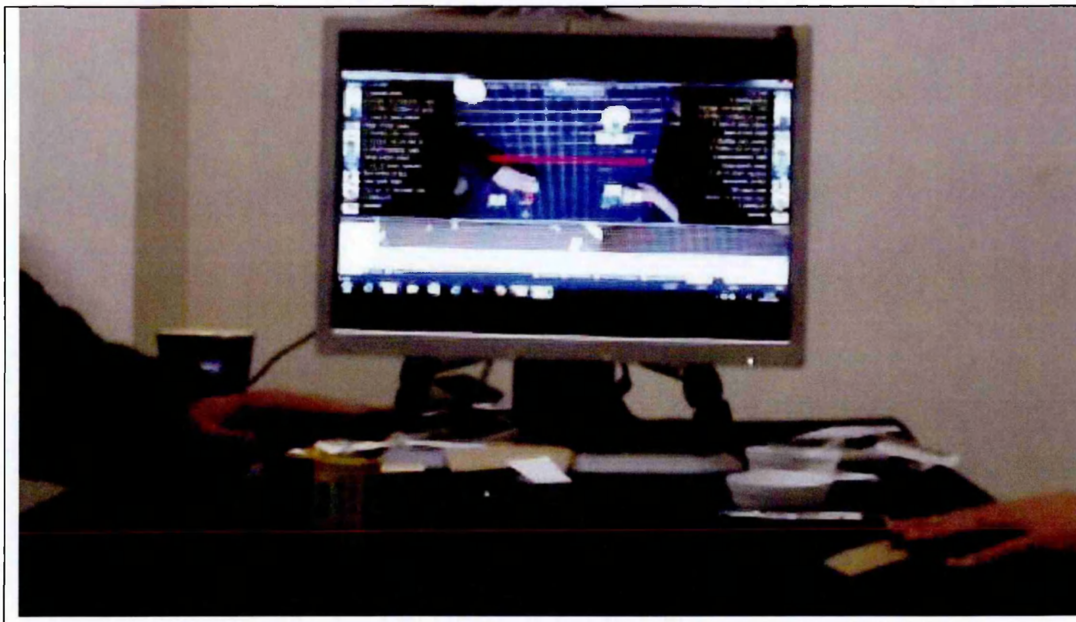


Figure 12 – Kolab in use.

6.2.3 Open Questions

At the end of each session users were asked what they liked and disliked about the system they had just used. All commented on the novelty of the experience describing it as 'fun', 'novel' and 'interesting' and there were a lot of positive comments about the general style of interface for example, '..nice collaborative working tool… moving things around on the table and taking things in and out…' (session 12); '… i liked the idea of moving stuff around…' (session 11); '… the idea that the table is my mouse mat and this tea bag is now my mouse is fantastic' (session 10); 'like the fact that you can engage with it in terms of physical objects', '[like]using inanimate objects that you can control and change around', '[like] you can explore… better interaction with our fingers… dealing with real world objects' (all from session 8); ' as a kinaesthetic learner [the idea of moving things] worked well for me' (session 7); 'its good to be able to put anything in there' (session 6).

Although these comments indicate a positive attitude towards the general idea of tangibility, many other comments concerned the perceived usefulness of such a system in the workplace and the use of improvised tangibles with a monitor. These '*What is it for*' style questions came up in sessions 3, 6,7,11, and 12. Some users commented that although they found the UI style itself appealing they could not see an immediate use for it in the workplace; Two commented on potential software design tasks that may benefit including UML diagramming and system architecture planning.

Users in five sessions commented on the use of a monitor to provide system feedback and the issues it caused. Some users felt that the correlation of the physical objects to the value in the system was too remote and made the operation of the system overly complex (sessions 6,7,10, 11, 12), some examples of this type of comment include a participant in session 11 who noted that the system was '*not great with a screen as I'm not looking at my partner all the time*' and a participant in Session 12 felt that the overall interface style was complex with '*too much going on, concentrating on hands, the table, areas of table and the screen*'.

6.3 Interaction Design

During the user study a number of observations regarding the interaction design were noted. Whilst a detailed examination of the interaction design is not a focus of this current research we briefly present some results which may help inform future iterations of Kolab or the design of similar systems. Firstly we present results which emerged regarding the use of slider controls and gestures to navigate aspects of the Kolab system. Secondly, a selection of comments is presented to illustrate both the positive and negative feedback that was given during the user study sessions.

Appendix J provides a more detailed description of Kolab's performance during the user study.

6.3.1 Navigation Styles

As part of the user study questionnaire participants were asked to choose which navigation style (tangible slider or gestures) they prefer. The overall result was not conclusive with a 50-50[1] split between those who preferred gestures and those who preferred the tangible control to navigate the lists of digital values (see chapter 3).

When using the slider control the implied spatial constraints partitioning the surface into 'data' and 'control' spaces did cause some temporary issues for users when using the tangible controls. In a small number of cases (sessions 1,4 and 5)users slid a control artefact into their partner's control space and began navigating the others list causing confusion for both participants for a brief period of time but this was soon corrected. The users in Session 10 commented that the switch of attention from the table to the gestures and back was a distraction, whereas the slider allowed the table to be the focus of attention. This may be due to the distant embodiment of the system. Projection onto the table may overcome this issue.

The alternative navigation method of free-air gestures also introduced a small number of problems. Some users specifically raised the issue of fatigue (sessions 1 and 3) making comments such as 'very tiring' and 'phew'. The exaggerated style of the gesture was also commented upon by users; For example, users in sessions 1 and 3 observed that the gesture required too much user action for too little system reaction.

Two users did attempt some unsupported gestures during the familiarisation phase of the sessions (see figure 13 below). One user in session 5 attempted a series of arm movements and waves to interact with Kolab imitating behaviour observed when gamers use the Kinect as a game controller. It transpired that this user had a Kinect at home and wanted to see if Kolab responded in a similar way. Another user, in session 12, tried an 'enlarge' gesture, similar to the 'pull apart

[1] 21 responses, 9 users preferred gestures, 9 preferred sliders, 2 liked both equally and 1 did not like either method of navigation

with hands' gesture used in [Wobbrock 2009]. The same user also tried to use his iPhone as an artefact later in the session, suggesting it may have been an instinctive reaction to try to do something on the surface.

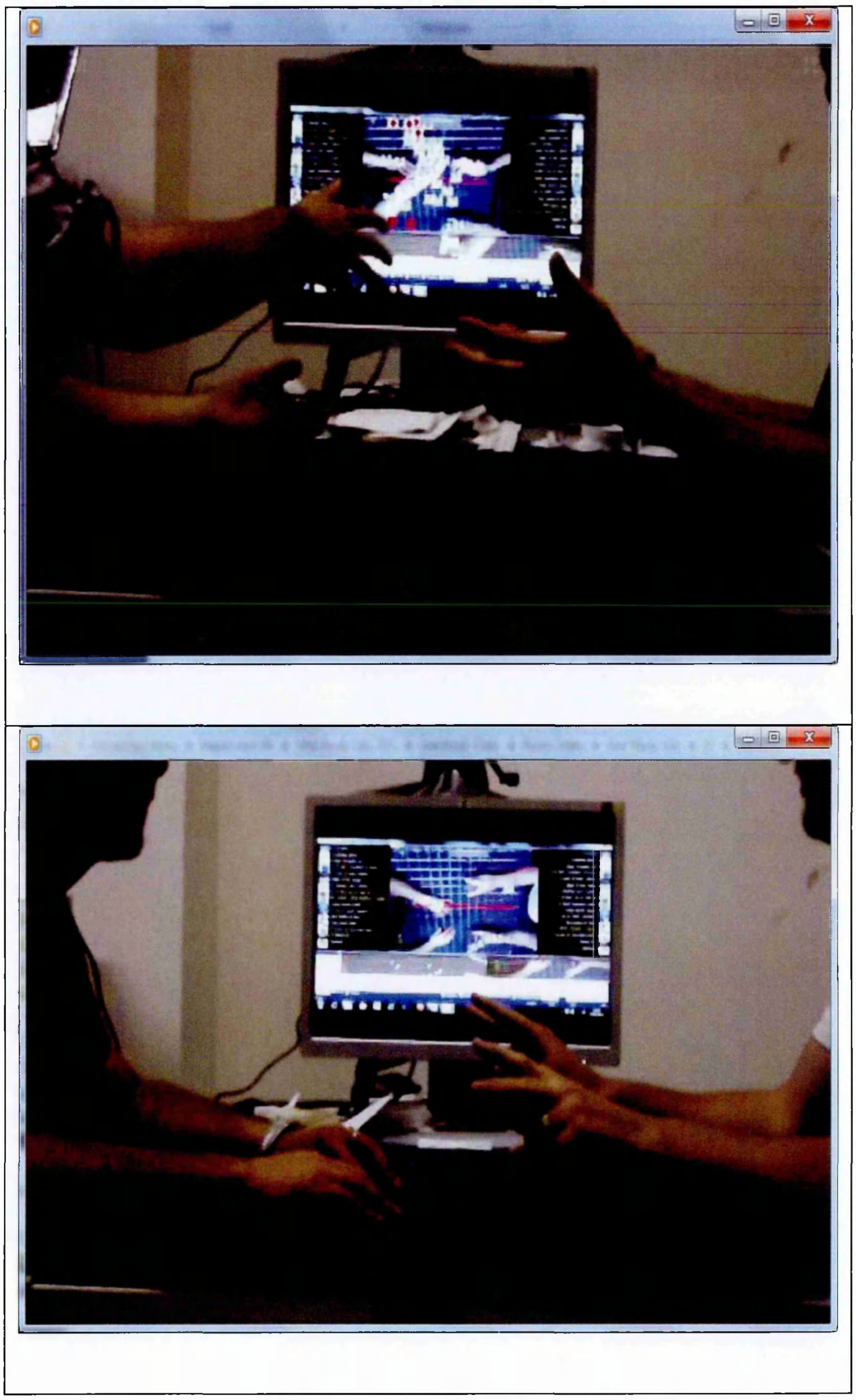


Figure 13 – Unrecognised Gestures

6.4 Results

The following table summarises the outcomes of the quantitative evaluation:

Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?		
Refined Question from Chapter 4	Measurable Statement	Result summary
Can users complete a collaborative task using improvised tangibles?	*Using improvised tangibles a significant majority of sessions will fail to construct solutions to the given task within the time allowed*	100% of sessions completed the collaborative task by agreeing a solution.
Are participants willing to use improvised tangibles?	*Only a minority of sessions (if any) will attempt to use items available outside of the object pool e.g. objects brought by in users or those away from the immediate are brought over onto the surface.*	75% of session attempted to add to or alter the initial object pool.
Will users find such a system easy to use?	*Due to the lack of representational significance and distant embodiment of system feedback users will find the system difficult to use and as such will return a low overall usability score.*	The overall SUS score of 65.5 was slightly below the mean score of 68
Will users find such a system easy to learn?	*Due to the lack of representational significance and distant embodiment of system feedback users will find the system difficult to learn. The average score for SUS questions 4 and 10 (learn-ability) will be low.*	The modal averages for the 'learnability' questions were 4/4 for SUS4 and 3/4 for SUS 10 (both on a scale of 0..4). Both responses can be considered to be high scores.
Will collaboration be encouraged?	*Users will rate their own contribution as low and their partners as high, indicating inequitable levels of participation.*	On average users rated their own and their partner's contributions as equal.

Table 11 - Quantitative Evaluation of Kolab - results summary.

The quantitative results show that all users managed to complete the collaborative task. This result suggests that using improvised tangibles in a collaborative setting with distant embodiment is not a limiting factor to completing such a task. Such a view is strengthened by the result that during the study we saw that one or more users attempted to improvise by modifying or adding to the seeded object in a majority of the sessions. Also, the usability score was near average and the learnability score was high which suggests that the users had no real difficulty in learning and using the system. From the survey responses asking participants to rate their own and their partner's level of contribution to the solution, it appears that an equitable level of participation was supported. Equitable participation is often considered a desirable state (from [Marshall 2008]) and can indicate that collaboration is encouraged or at least not inhibited. Further evidence of the effects Kolab had on collaborative behaviour during the study become apparent from analysis of the user study videos and participant comments. To help analyse these behaviours two issues from the literature are worth noting. Firstly, when investigating sharable interfaces, Fleck, Rogers, Yuill and Marshall [Fleck 2009] identified that collaborative discussion is indicative of collaborative behaviour. Secondly, Hornecker, Marshall, Dalton and Rogers in [Hornecker 2008], highlight awareness as behaviour indicative of collaboration. Similarly, Fleck et al [Fleck 2009] suggest that awareness is a coordinating behaviour in collaborative work.

In order to further explore how the Kolab prototype supports collaboration we shall revisit these ideas of equitable participation, collaborative discussion and awareness in the context of the user study sessions.

Equitable Participation:

Key to Kolab's design was the implementation of multiple entry points. This design enables collaboration by allowing everyone to participate in using the system at once if they so wish.

The survey questionnaire included two questions (q11 and q12) which asked each participant to rate the extent to which they felt they contributed to the overall solution and also the extent to which they felt their partner contributed (see 6.1.4). On average, participants rated the levels of contribution to the solution as equal. This suggests that, overall; the use of the Kolab system did not adversely affect collaboration because, on average, contributions were regarded as equitable.

The conclusion from the survey responses described above is backed up by video analysis which shows that in 11 of the 12 sessions users interacted with the system in parallel, taking advantage of the availability of multiple access points and interacting with (different) tangible artefacts at the same time; a common pattern of usage was where the participants would agree a course of actions (e.g. "You get the rum and I'll get the fishing kit") and would then carry this out in parallel. In the one session where parallel interaction was not evident (session #11) a participant delegated most of the system operation to his partner early in the session after attempting but failing to use the system because a bandaged hand prevented the user from operating the slider control effectively. The user did participate in discussing a solution.

Although no session agreed a strict turn taking strategy (where each participant in the session used the system in agreed rotation), when users agreed what to do through collaborative discussion a number of behaviour patterns emerged including working the system in parallel and in series. These collaborative discussions are explored next.

Collaborative discussions:

Fleck, Rogers, Yuill and Marshall [Fleck 2009] suggest that 'making and accepting suggestions' is an example of collaborative discussion. This was very much in evidence during each of the user study sessions. In all 12 sessions participants talked and worked together towards a solution by first agreeing a course of action verbally then carrying it out using the Kolab system. Looking more closely at this general pattern some subtle differences became apparent.

Users in a majority of sessions (11 of the 12) followed a similar pattern of behaviour when agreeing and actioning a solution. In this pattern of behaviour users gradually built up an agreed solution by verbally agreeing one or two items at a time. When only one item was chosen polite turn taking was evident (as perhaps would be expected with adult users in a work environment) otherwise the system was used in parallel.

Once the items were programmed and on the surface they returned to discussing what else was required.

The behaviour pattern just described occurred in all but one session. In this session (#8) the two participants discussed the options available, agreed on *all* of the items to take and then split it up 'you take the items in the top half of the screen and I'll take bottom half of list'. They then operated the system in isolation to get the required objects with little further verbal contact.

In addition to 'making and accepting suggestions', Fleck et al[Fleck 2009] also suggest that 'negotiation' is given as an example of collaborative discussion. 'Negotiation' is defined as behaviour where participants engage critically and constructively with each other's suggestions. Whilst participants discussed the items to take there was very little evidence of suggestions being analysed critically during the session.

Awareness of each others actions:

Awareness can be described as "*an understanding of the activities of others, which provides a context for your own activity*" [From Hornecker 2008 page 168]. Parallel activity is seen as a positive awareness indicator and this did occur (see 'Participation' above) but of more interest perhaps is the occurrence of negative awareness indicators attributable to a particular property of Kolab, that of distant embodiment of feedback[Fishkin 2004].

There was evidence to suggest that the use of distant embodiment had a negative impact on *awareness* of participants to each others actions. A number of users commented on the level of concentration required to continually refer to the monitor screen. Users in five sessions commented on the use of a monitor to provide system feedback and the issues it caused. Some users felt that the correlation of the physical objects to the value in the system was too remote and made the operation of the system overly complex (sessions 6,7,10,11, 12), some examples of this type of comment include a participant in session 11 who noted that the system was *'not great with a screen as I'm not looking at my partner all the time'* and a participant in Session 12 felt that the overall interface style was complex with *'too much going on, concentrating on hands, the table, areas of table and the screen'*. The users in Session 10 commented that the switch of attention from the table to the gestures and back was a distraction, whereas the slider allowed the table to be the focus of attention.

In addition to user comments, the impact of this can be seen by incidents of *interference* occurring during user interaction. When using the slider control the implied spatial constraints partitioning the surface into 'data' and 'control' spaces caused some temporary issues for users when using the tangible controls. In a small number of cases (sessions 1,4 and 5) users slid a control artefact into their partner's control space and began navigating the others list causing confusion for both participants for a brief period of time but this was soon corrected as participants recognised what was happening and corrected their behaviour. Generally the users used the screen image to identify where the spatial constraints where but a user in one session used artefacts that took on no digital value at all. The user (in session 11) used the affordances of artefacts to provide a physical guide to the implied spatial constraints. The user placed 2 artefacts (a ticket and a postcard) on the surface to provide a physical guide to the location of the control zone (see figure 11).

The data presented above suggests that, within the constraints of the chosen task, collaborative efforts are supported by Kolab and that the user interaction design does not impair collaborative efforts to the extent that a collaborative task cannot be completed. But, as identified above the use of distant embodiment did cause some temporary issues with users interfering with others activities, these issues were soon corrected by the users once the interference was identified.

Recall that an additional goal of this current research was to explore the technical issues that become apparent when realising a TUI based on improvised tangibles. This chapter concludes with an analysis of the objects users selected to use and not use as artefacts as well as summarising the technical performance of the prototype.

With regards to the question *'What sort of artefacts do users prefer to improvise with?'* the qualitative data collected during the study showed that coffee cup tops, tickets and paper were the most popular medium for artefacts from a seeded pool. Both coffee cup tops and paper were used extensively as slider controls as well as artefacts representing data items. Highly reflective and small items caused the most significant computer vision issues. For example, highly reflective surfaces such as coffee cup glaze and cigarette packets created multiple tracking targets that 'jittered' significantly as the reflected light moved, and small items such a cuff links and pens/pencils were rejected as 'noise' due to the object filtering thresholds employed. The affordances suggested by the items available did not appear to cause confusion, but in a minority of cases, the equipment and use of gestures did appear to cause confusion. An example of this was noted earlier in section 6.3.1, where two users attempted additional unsupported gestures during the familiarisation phase of the sessions. One user attempted a typical touch screen 'expand' gesture and another used gaming style gestures.

When considering the question *'What sort of artefacts do users choose not to improvise with?'* we can look to the additional survey conducted after the user study sessions. This survey suggest that although personal items such as wallets and security passes are regularly taken in to meetings users may not choose to present them as tangible artefacts in a collaborative setting.

Finally, at a technical level, the prototype system worked well enough to explore the use of improvised tangibles in a collaborative tangible user interface. However, issues with object detection, tracking and the sensitivity to ambient light mean that it would not be suitable in its current state for unsupervised use by participants. Optical sensors offer a portable, ubiquitous, foundation for nomadic interactions, but the environment requires a level of control that may be impractical at this stage. Appendix J gives a report on system performance during the user study.

Before summarising the conclusions from this result set, we will address some possible limitations with the study design in the following chapter.

7 Limitations of the study

This chapter identifies some potential issues with the study design presented in preceding chapters and addresses them where possible.

7.1 External Validity

A number of factors may limit the extent to which the findings presented in this current research may generalise to a wider population. Firstly we shall consider the make-up of the group of participants used in the study and then explore the effects that the novelty of the experience may have on the results. Finally we consider the realism of the task the participants were asked to perform.

The study group was self-selecting from a single department within an NGO. Resource for the research was limited and the study group represented working professionals willing to participate in a user study and included a mix of male and female workers.

It is worth noting that the study group included some colleagues of the researcher. Of the 24 participants the researcher has directly worked with 5 participants and personally knew (at the start of the study) another 6. This may have introduced an 'Experimenter effect' where nuances in the way the user-study was conducted by the researcher with different colleagues may introduce bias into the results. Similarly it is possible that the participants modified their behaviour to accommodate a perception of what the researcher's expectations. Brown, Reeves and Sherwood [Brown 2011] describe this as the emergence of *demand characteristics* in a user study. In order to counter this, each session was conducted according to the same scheme.

The study required participants to break off from the normal day-to-day activities to specifically take part in the study and use a novel user interface. In such circumstances the 'Hawthorn Effect' is likely to become a factor: in other words subjects may respond to the special attention and novelty of an experience. The *'demand characteristics'* mentioned above from [Brown 2011] are also related to this effect. Tangible interaction, especially of a kind employing improvisation, is not a common experience in the workplace so it would be difficult to remove this factor in the present study.

As previously mentioned in section 3.6 the task chosen was designed to represent certain characteristics of a collaborative task requiring tangible interaction that would appeal to a wide range of subjects within the available time but could not be said to represent the work-day roles of any study group member.

The task was a simple closed task, in that it had a fixed range of 16 values users could employ in the scored solution along a limited range of locations in which artefacts could be placed on the surface (effectively in or out of the lifeboat). The closed nature of the task is probably not truly representative of collaborative tasks undertaken in the workplace where more open or design based tasks with no definite end-point are possibly more typical.

As discussed in [Lew 2011] this lack of applicability may impact external validity by introducing a boredom factor where participants are not engaged in the outcome. This is potentially true of this user study, and several comments from users questioned the realism of the task (section 6.3.2). For the purpose of answering the research question the quality of solutions was immaterial, it mattered only whether some solution was constructed. This may have limited the impact of the boredom factor on the results by only relying on the occurrence of a solution rather than its quality. But, when considering the applicability of the task the lack of negotiation between participants in the study cannot be ignored; as presented in 6.4 above there was a lack of evidence to suggest true critical discussions took place during the study as users constructed their solutions. This lack of negotiation may demonstrate the impact of the artificial nature of the task on the results and crucially, the artificial nature of the task may limit the generalisation of the results beyond the scope of the study described in this research.

7.2 Internal validity

Certain aspects of the study design may have influenced the study results; of particular relevance is the use of a seeded object pool (described in Chapter 5).

The study design relied upon a seeded pool of objects found within the study room. This, by definition, was restricted to items available in the room. Although this restriction helped to ensure an ecologically valid set of 'real-world' objects, it could not be claimed that the variety was exhaustive or even representative. The number of each item type was not controlled and the state of the object pool was not reset to a standard arrangement at the end of each session. Items added to the pool by users were left in for later sessions. Other than identifying commonly used item types this current research presents the items used in the sessions but does not attempt to draw generalised conclusions from the artefact choices themselves or the frequency of usage.

7.3 Construct Validity

Bias in subject responses in the form of 'the Hawthorn effect' has already been mentioned above. A similar effect known as the 'Pygmalion Effect' must also be considered as a form of researcher bias. The use of open questions and evaluating video of the study sessions may introduce bias from the researcher, and a 'Pygmalion Effect' introduced where the researcher brings in real-life expectations and the study becomes a self fulfilling prophecy. This occurs by concentrating on the responses that the researcher is expecting or wants to hear and sub-consciously ignoring less appealing responses. As a result, this may lead to open question session being 'directed' in a desired direction and the subsequent analysis of the results being selective.

To counter such a possibility open question sessions were conducted with minimal input from the researcher. However, to promote discussion, the researcher did contribute some unplanned and inconsistent input to all open question sessions. In reporting the results of these sessions (see chapter 6.2.3) a balanced view of the comments and user behaviour is presented, highlighting positive and negative views of the experience.

8 Conclusions and contribution to knowledge

8.1 Conclusions

Returning to the central research question posed in Chapter 1 - *Does poor representation significance of user selected objects have a limiting effect on the usability of the tangible interaction enough to limit the viability of an improvised tangibles based system for co-located collaboration?* The formal user study in the current research has presented evidence consistent with the view that a system such as Kolab is not unusable when participants use arbitrary improvised tangibles over short periods to complete a collaborative task. This leads us to the conclusion that an interaction design based on improvised tangibles with poor representational significance and distant embodiment of feedback does not have a prohibitive effect on usability. The results suggest that the interaction design presented in this research, in the context of the limited and artificial task, does not affect usability to the extent that collaboration is impaired. However the distant embodiment of feedback in the Kolab setup did cause some temporary interference issues for a minority of users. This interference may be viewed as a negative awareness indicator [Hornecker 2008]. Such interference was temporary and did not appear to prevent participants from constructing a solution together as overall participants rated their own, and partner's, contributions as equitable.

As well as demonstrating that users do appear capable of using improvised tangibles in a collaborative context the study also showed that these tangibles were multi-functional. The study showed that the tangibles used exhibited *low viscosity* [Edge 2006b] and *low rigidity* [Edge 2006b] as the tangibles took on different values and functions both across different sessions as well as within the same session. For example the same tangible type (e.g. coffee cup lid) was used as both data items and controls.

Despite the variety of tangibles used during the study there was no evidence of personal items being used as tangibles. The additional email survey conducted after the user study showed that personal item such as security passes and wallets are commonly carried into meetings but were not used during the present user study. This suggests that personal items may not be widely employed as tangibles in a collaborative workplace environment and that speculation as to the use of personal objects in similar single user systems from [Carvey 2006] may not carry across to sharable interfaces.

On a technical note, the variety of items that users attempted to use as tangibles did cause some problems in the object recognition and tracking elements of Kolab. To help overcome this technical limitation we may give further consideration to the objects that were used in the study. During the study it was observed that many users enter a meeting room with stationery and refreshments. The study also showed that users were comfortable using items such as coffee cup tops and stationery items when they are available in a pool of objects. Given the computer vision issues discussed earlier future designs may benefit from concentrating on recognising and tracking these two classes of items rather than attempting a more general object recognition and tracking scheme.

8.2 The contribution to knowledge

Within the constraints of the task chosen for the user study this current research has demonstrated through a 24 participant user study that an interaction design based on improvised tangibles with poor representational significance does not impair collaborative efforts to the extent that a collaborative task cannot be completed despite a) the lack of augmentation (such as labelling) on the tangibles to suggest their underlying digital values and b) the use of distant embodiment of system feedback. This has begun to fill a gap in the knowledge regarding the use of improvised tangibles for co-located collaboration using tangible user interfaces.

Additionally, this research has contributed the data from an additional survey showing the types of artefacts participants may choose to use in a workplace setting and which artefact types they may not opt for (section 6.2.2). This may inform the design of systems similar to Kolab which are based on improvisation of tangibles.

Finally, the current research has also realised an interaction mechanism which allows tangibles to be improvised in a multi-user co-located collaborative environment. The key design challenges faced by this interaction style have been described (chapter 3). By implementing a similar interaction mechanism, future nomadic tangible interfaces can use improvised tangibles and dynamic binding to support artefacts that have high viscosity and low rootedness. In practical terms such system could be more portable and not rely on fixed sets of tangibles to be maintained.

It is worth noting that a large proportion of the findings presented in this current thesis have been presented at the ACM conference "Design In Software 2012", in Dalton, Mackay and Holland's paper 'Kolab: Appropriation and improvisation in mobile tangible collaborative interaction"[Dalton2012].

9 Further Work

The current research developed a working prototype TUI system based on using improvised tangibles in a collaborative task. In this chapter a number of additional areas of research are explored that may take the current research forward in a number of ways. Firstly by exploring the limits of the Kolab interface style both in terms of usability and the types of applications that may be suitable. Secondly by looking at the technical issues associated with enhancing the technical aspects of the prototype and finally, the chapter concludes by looking forward to TUI devices that support multiple applications in a way we have come to expect from GUI interface styles.

9.1 Additional Studies examining the impact of abstract objects on the interaction

The current research has demonstrated that a simple non-trivial task can be completed by a pair of users collaboratively using improvised tangibles with poor representational significance. Further studies, using the same task or a similar one, could investigate a number of additional aspects of representational significance

One such study could investigate whether users naturally choose tangibles with close representational significance over more abstract ones. This could be done using a task similar to the one used in the current research but with deliberate manipulation of the seeded object pool (see Chapter 5). The pool could be kept constant over all sessions and offer objects with strong and weak metaphors for the underlying digital values. From this an analysis of the object choices and the digital values they are chosen to represent could be done.

This proposed experiment idea raises questions of how *'representational significance'* should be measured. Fishkin [Fishkin 2004] offers the 'metaphor' axis of his classification framework. This could be expanded upon with ideas from other fields, for example psychology, to derive a more operationalised definition of this term.

Another possible experiment could look at the level of recall of association over time. One possible advantage of a TUI where the tangibles have high representational significance is the increased learnability of the associations and de-emphasis on having to recall associations made in previous sessions. It may be interesting to develop an experiment to test the extent of users' recall of associations of abstract objects to digital values over multiple sessions and timeframes. Repeated use over multiple sessions by a group of users would also provide an opportunity to examine whether there are common associations made between digital and physical artefacts. [2] The number of users working collaboratively could also be varied to explore what limits, if any, exist on the size of the group and the ability to recall associations.

Moving on, recall that Chapter 7 recognised the possible impact on the results of this current research due to the artificial nature of the task used in the user study. This suggests that a set of further studies should concentrate on a richer task over a longer period for a smaller user group. Some proposals for further work related to richer tasks and longer periods of exposure are presented in the next section.

9.2 More complex open ended tasks

One potentially rich area for a system like Kolab is in open-ended design applications such as kitchen design or software design. For these design activities the design process can be supported by the arrangement of artefacts on a surface to represent a plan or schematic, e.g. a kitchen floor plan or a software diagram (for example a class diagram, database schema or screen design). A nomadic system is suitable because these activities may be performed in multiple locations, for instance a kitchen designer visiting people's homes or a software designer meeting user groups.

[2] Thanks to the DIS2012 reviewers for this suggestion.

Additionally, these activities may be collaborative with multiple customers or users being directly engaged in constructing an agreed design. Importantly for this proposed research each application may require multiple palettes or classes of artefacts such as different kitchen furniture ranges or software components which could be represented by a single, initial, artefact set. Furthermore these artefacts may need customising to handle bespoke kitchen units or specific software components or simply need replacing which would enable the practical use of improvised tangibles to be examined.

Richer applications would potentially require the interaction design presented in this current research to change. For example, in order to make such applications more practical the 'distant embodiment' of output employed so far would need to be reconsidered. This is considered in the next section.

9.3 Adding Projected images

One obvious change to the current set-up would be the introduction of closer embodiment of output. Recall that the user study design used an external monitor for user feedback (an example of 'distant' embodiment of output using Fishkin's taxonomy, see section 2.2) this could be brought nearer by projecting a variation of the feedback image directly on to the surface. For example, the lists of available digital values could be projected on to the control areas and the location of the slider control on the projected image used to select a digital value (or remove the slider all together and just use touch gestures). Additionally iconic images of the digital values associated with physical objects could be super-imposed directly rather than on-screen.

It is perhaps worth noting that combining computer vision with projected images is not without issue when using a single surface. Previous systems that have used projected output with computer vision have required additional techniques to overcome the interference of the colour projected image with the captured colour images. This problem is known as 'visual echo' or visual feedback' [Junuzovic 2012]. Hardware solutions are common as they offer a reliable method of overcoming this 'echo' without impacting software processing performance. Example systems that rely on hardware solutions include Visual Touchpad [Malik 2004] which increased the camera gain and 'Bonfire' [Kane 2009], 'Portico' [Avrahami 2011] and 'PlayAnywhere' [Wilson 2010] which all use hardware filters. Another possible solution is to switch off the projector at the time of image capture. This method of time-multiplexing has been demonstrated in [Junuzovic 2012] using a hardware circuit to synchronise the camera and projector. Software solutions to the problem of visual echo also exist for example as presented in [Liao 2008] where image subtraction is used to remove the projected image from the input frames but this solution, according to [Junuzovic 2012], is not robust.

The previous sections have looked at continuing with the general research direction presented in this current research, generally assuming a single application is in use. We now move on to consider an additional area of research that potentially leverages the flexibility of improvised tangibles to realise TUI that seamlessly supports multiple applications.

9.4 Multi-Application TUI

Although not demonstrated in the current research it is feasible to assume that a future nomadic tangible device will run multiple applications and that improvised tangibles can be shared between these applications. A certain level of artefact flexibility has been demonstrated in this current research and this flexibility suggests that such sharing of tangibles between applications is possible but the availability of multiple applications may introduce further interaction design issues. In a GUI system users can easily swap between applications. However, the ability to '*support[ing] fluid transitions between activities*' [Scott 2003, page 1662] becomes problematic in table-top TUI systems due to their inherent physicality. As well as switching applications, shared systems may also need to consider views within the same application. This behaviour was suggested by a recent study ([Marshall 2011]) which demonstrated that multi-use may occur in a '*staggered way*' rather than users gathering at the same time. Considering these scenarios, future research questions may consider whether the use of flexible improvised tangibles can contribute to the design of tangible systems capable of such switching and if so, how could this be realised?

10 Closing Remarks

For a nomadic general purpose tangible based system to be useable and supportive of impromptu collaboration we looked to design a system which would permit a very wide range of objects to be appropriated and used as tangibles. The technical approach of Kolab, using a fusion of depth and image sensing has shown it is possible to use arbitrary objects as improvised tangibles.

Given the core TUI literature (for example [Fitzmaurice 1996], [Holmquist 1999], [Ishii2008], [Ullmer 2000]) it was doubtful that a system based on improvised tangibles with little or no '*representational significance*' [Ullmer2000] would be usable in a collaborative context. The current research has demonstrated through a formal in-the-field user study with 24 participants that poor representational significance does not appear to impair collaboration. The user study results also suggest that speculation as to the use of personal objects in similar single user systems from [Carvey 2006] may not carry across to shared interfaces.

There is no suggestion that such arbitrary artefacts are better than carefully designed or labelled artefacts but by demonstrating that they are not necessary opens the way for nomadic TUI systems that do not require pre-programmed, augmented (with labels or electronics to aid object recognition by the TUI system) or specific tangibles. Users working with such systems can introduce artefacts as required to support the need for additional tangibles or to replace lost tangibles and these tangibles may be potentially used across applications.

Overall, we have shown that improvised tangibles used with a nomadic platform can overcome issues of flexibility and bulkiness and that poor representational significance is not a barrier to co-located collaboration.

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Appendices

Appendix A – Invitation to participate email

Gordon

At the moment I can do the following:

	10-11	11-12	12-1	1-2	2-3	3-4
Mon	Y	Y	Y	Y	Y	Y
Tue	Y	Y	Y	Y	Y	Y
Wed	N	Y	Y	N	N	N
Thur	N	Y	Y	Y	N	N

I'll let you know if that changes.

Regards

<footer removed>

From: MACKAY, Gordon

Sent: 13 June 2011 09:14

<to list removed>

Subject: Call for volunteers for a user study - 4th July-7th July

Hi everyone

As you may (or may not) remember I am doing an MPhil and need to conduct a user study so if you can spare an hour sometime during 4th July - 7th July in Swindon to participate that would be great.

I need about 30-40 people and you will be asked to work in pairs to use a prototype table-top system so that I can see what is good/bad about it and how people use it. (it isn't testing so please expect the software to break etc.!).

As you can imagine this will need a bit of organisation so if you are interested can you reply to this email and let me know your availability

By putting a Y/N in the grid below (don't worry about formatting it)...

	10-11	11-12	12-1	1-2	2-3	3-4
Mon	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
Tue	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
Wed	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
Thur	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N

so I can work out who is available and when and then I can draw up a timetable.Please let me know by **Monday 20th June so I can get a provisional timetable out by Wednesday 22nd June.**

If you volunteer

- You will be asked to attend a prearranged slot in the Swindon I.T. Training room to use the system (with another colleague) in a number of configurations. You will be videoed so I can analyse the sessions off line and the results will form part of my thesis as well as (possibly) published papers, but no individuals will be identified in any published work or thesis.

- You will also be asked to complete a 'usability' survey - again this will be anonymous.

Just to be clear this is my MPhil and nothing to do with EH. Chris has kindly agreed to this and it is my PDL I am using , but please check with your team leader etc that its OK for you to attend and don't claim T&S if you are travelling!

When I know who can make it I shall send out more info on what its all about.

Cheers

Gordon.

Appendix B –Informed consent Form

Project Title	**Improvising Tangible User Interfaces for Informal Collaboration**
Why is this research being done?	This research is being conducted by Gordon Mackay for research towards his Masters Degree (MPhil) currently being studied through the Open University and is not associated with English Heritage. The research is investigating how a novel table-top user interface can be developed and used within the workplace; As part of this research a user study is being performed during which pairs of participants will be asked to collaborate to agree a solution to a shared problem. As well as looking at design and usability issues of the user interface the research will also look at how the user interface itself affects the collaboration between participants by looking at user behaviour as the task is completed.
What will I be asked to do?	Each session will last approximately 60 minutes. The procedures involve asking pairs of users to play a simple

	computer game using a novel table-top user interface. The interface will be configured in a number of ways during the session and users will be asked to play the game twice within a session. During the session users will be asked what they like and dislike about the interface. After the session you will be asked to complete a questionnaire. In order to accurately record user interactions each session will be videoed for later study.
What about confidentiality?	This research involves collecting raw data for later analysis. • We will be making video recordings of each session in order to accurately record user behaviour for later analysis. • Questionnaires will also be completed by participants during this research.

	• The researcher will take ad-hoc notes during each session. Such raw data from the research will only be shared with research team members, research supervisors and/or approved representatives of the Open University. Raw data will be stored on password protected personal computers or servers. Video clips, stills, quotes and subsequent analysis of the raw data may be used in publications but will not be attributable to individuals since we will take reasonable steps to remove personally identifiable information such as names or uniquely identifying characteristics. **Please tick here ____ if you do NOT wish to be videoed.** **By signing this form you acknowledge that we can record and analyze the session and use quotes, video clips and still pictures in publications after they have been made anonymous.**

What are the risks of this research?	There are no known risks associated with participating in this research project.
What are the benefits of this research?	This research is not designed to benefit you personally but the results may help the researcher learn more about how novel user interfaces can be designed and how they are used by users outside of an academic environment for collaborative tasks.
Do I have to be in this research? May I stop participating at any time?	Your participation is completely voluntary and you may stop participating at any time.
What if I have questions?	If you have any questions please contact Gordon Mackay at : Gordon.mackay@english-heritage.org.uk
Statement of Age of Subject and consent	Your signature indicates that; you are at least 18 years of age; the research has been explained to you to your satisfaction; and you freely and voluntarily choose to participate in the research project.
Signature and Date	

Appendix C – Participant Briefing Notes

Introducti on	5 mi n.	All OK on Informed Consent form? Research into improvised UIs for informal co-located collaboration. This weeks experiment is investigating how WORKPLACE users use such a system to solve a shared problem; I will be trying to measure the type of behaviours this interface style promotes and collect useful information on how future systems may be designed. Also interested in the sort of everyday objects that may get used when improvising a UI in an office environment. We will be using the tabletop and everyday objects to extend the UI by improvising a Tangible User Interface using a computer vision based system, a camera and a notebook PC. And using this interface to play a teambuilding game which requires you to agree a solution to a problem. This research is a part of a wider effort to look at new ways for us to interact with computers; for my research its about alternatives to

		a keyb/mouse and using the spaces available and objects around us when we work together Not testing it but looking to see what works and what doesn't and how users interact with both the computer and each other using this style of UI. It is a prototype to help investigate the style of interface and not a finished product, don't expect to be using it any time soon. In-situ User study is important as it allows researchers to **quantify** in some way what is good and bad and put it into a context for other researchers to understand. For this reason all session have to be as identical as possible so that in my analysis I am comparing like-for-like. Please enjoy yourself and relax! So what's going to happen in the hour.. After a familiarisation session you will be asked to play a simple 'team building' game together. Play twice with the system in two

		configurations. I am interested in what such a system MIGHT need to cope with so … When playing please feel free to use whatever is to hand from the piles of things in the room, pockets or bags and even leave the room if you wish to get things for outside the room.
Familiarisation	10	Finger tracking Tangible Artefacts Sliders Click/Double click and Lists Buttons to complete Explain game…. Sinking Ship • Middle of ocean • Need to agree what to take on motor-less dinghy to survive until rescued or land found • Select items in list and assign them to the artefacts • Slide 'over the line' to put in the dinghy

		• Each item has a nominal weight and there is a weight limit of '15' in the dinghy– see real time display • Agree the solution between you
Game session #1 – With TUI Sliders	15	Allow users to play the game and say when done.
Open Questions	5	How did you find that? What did you like? What did you dislike?
Game session #1 – With Sweep gestures	15	Replace TUI slider with sweeping gesture.
Open Questions	5	How did you find that? What did you like? What did you dislike?
Explain Questionnaire	2	Please complete questionnaire ASAP after the session
Close	3	Thanks

	60 mi ns	

Appendix D – Participant Questionnaire (completed sample)

First of all, thank you for taking the time to take part in this study and answer these questions. Many are answered with a 'sliding scale' so please choose the answer that best suits you; use the gaps under the tick boxes for any comments.

Once again, thanks. Gordon.

About You:

Gender	Male
Left/Right Handed	Right
Role/Job Title	Developer
Where did you sit?	Facing the whiteboard

Portable TUI System Prototype – Usability Survey

1. I think that I would like to use this system frequently.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	X	☐	☐	☐

2. I found the system unnecessarily complex.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	X	☐	☐	☐

3. I thought the system was easy to use.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	X	☐	☐

4. I think that I would need the support of a technical person to be able to use this system.

Strongly Disagree 1	2	3	4	Strongly Agree 5
X	☐	☐	☐	☐

5. I found the various functions in this system were well integrated.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	☐	X	☐

6. I thought there was too much inconsistency in this system.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	X	☐	☐

7. I would imagine that most people would learn to use this system very quickly.

Strongly Disagree				Strongly Agree

1	2	3	4	5
☐	☐	☐	☐	☐

8. I found the system very cumbersome to use.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	X	☐	☐

9. I felt very confident using the system.

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	X	☐	☐

10. I needed to learn a lot of things before I could get going with this system.

Strongly Disagree 1	**2**	**3**	**4**	**Strongly Agree 5**
X	☐	☐	☐	☐

11. I contributed most to the overall solution

Strongly Disagree 1	**2**	**3**	**4**	**Strongly Agree 5**
☐	☐	X	☐	☐

12. My partner contributed most to the overall solution

Strongly Disagree 1	2	3	4	Strongly Agree 5
☐	☐	X	☐	☐

13. Have you ever worked with your partner previously?

Never 1	Occasionally 2	Frequently 3
X	☐	☐

14. Which method of navigating the list of items did you prefer?

Slider	Gestures	Neither	Both
1	2	3	4
X	☐	☐	☐

15. Any other comments.

I can imagine using it more with turn-based collaboration rather than both trying to achieve the same task simultaneously. We were both picking from a duplicate list of the same set of objects and it probably wouldn't have taken much longer for one person to "drive" as two.

That said; if there was a fixed set of items, such as with a jigsaw, then I can absolutely imagine using a system like this. You could then both work together, but with more autonomy due to less communication needed because of the lack of a requirement to manage two sets of lists.

As has been noted by others; the disproportion between gesture and on-screen movement was a little tiring after a while.

A single sweep that moved the list position from top to bottom would have been preferable to a sweep per item change. Also, not having the selected list item wrap from top to bottom (and vice-versa) would have made it easier.

I occasionally found myself veering off the slider section of the table due to going slightly diagonal, rather than just up and down. Some sort of on-screen feedback as to where you were in each area would be helpful.

Appendix E – Additional participant Survey email

Dear Colleague,

As part of a follow on from the user study I am interested in what items may have been used to improvise the user interface.

I am doing a retrospective study on what may have been used; to this effect could you take a minute to quickly tick/highlight what items you have in your pockets and also what you would typically take into a meeting?

Many Thanks

Gordon.

Keys

Security Pass

Coins

Notes

Credit Cards

Wallets/Purses

Membership/Other cards

Business Cards

Smart Phone/Electronic organiser/Phone

Receipts

Pens/Pencils

Notebook etc

Coffee/tea cup

Other Drink container

Bag

Appendix F – Additional Survey Response (sample email)

Gordon.

This is what I'd usually have in my pocketsssss................

Keys

Security Pass

Coins

Notes

Credit Cards

Wallets/Purses

Membership/Other cards

Business Cards

Smart Phone/Electronic organiser/**Phone**

Receipts

Pens/Pencils

Notebook etc

Coffee/tea cup

Other Drink container

Bag

Other (please state)

Appendix G – Lost at Sea Scoring

The original paper based 'lost at sea' task used as the basis for the proof of concept application described in chapter 3 requires individual participants to rank a list of 15 items in order of importance or usefulness to survival, they are then grouped in to 'teams' to collaborate and agree a single ranking which is then scored against a set of expert rankings.

In order to make the task more suitable for a user study using a tangible user interface a number of modifications were made to the mechanics of the task whilst retaining the overall goal of choosing and agreeing items for survival.

Rather than be a ranking exercise the participants in the study have to select which items to take from the available list, and conversely which items to leave behind in order to maximise their chance of survival and rescue. In order to constrain the choices each item is allocated a nominal weight value and the chosen set is subject to an overall weight-constraint that if users decide to go over, will sink the craft.

In its original form the each item has a rank (1 being the best,16 the worst) in the proof of concept application in order to prevent the top 5 items being selected and to encourage debate and discussion the weights were manipulated to ensure that by selecting them they would exceed a weight limit. By trial and error a set of nominal weights and weight limit of 15 were decided up; see table 2 below for details. The ideal solution has a score of 15 (based on the top 5 ranked items) but a nominal 'weight' of 16, the worst possible score within the weight limit (based on rank) is 109.

Item	Score	Weight	Ideal Solution	Worst Solution
A sextant	16	2		2

A shaving mirror	2	1	1	
A quantity of mosquito netting	15	2		2
A 25 litre container of water	4	5	5	
A case of army rations	5	5	5	
Maps of the Pacific Ocean	14	2		2
A floating seat cushion	10	1		1
A 10 litre can of oil/petrol mixture	3	4	4	
A small transistor radio	13	2		2
20 square feet of Opaque plastic sheeting	6	1		
A can of shark repellent	11	1		1
One bottle of Rum	12	2		2
15ft nylon rope	9	2		2
2 boxes of chocolate bars	7	3		
A fishing kit	8	1		1
Matches	1	1	1	
Total Weight		35	16	15
Total Score			15	109

Maximum Weight		15		

Table G.1 –Items to take into the lifeboat.

The 'best score' of 15 is subtracted from the participants' final score to gain a final survival score.

The bandings for the final survival score were as follows:-

Range	Rating	Message
0 – 25	Excellent.	You demonstrated great survival skills. Rescued!
26 – 32	Good.	Above average results. Good survival skills. Rescued!
33 – 45	Average.	Seasick, hungry and tired. Rescued!
46 – 55	Fair.	Dehydrated and barely alive. It was tough, but rescued!
56 – 70	Poor.	Rescued, but only just in time!

71 – 112	Very poor.	Oh dear, your empty raft is washed up on a beach, weeks after the search was called off.
score ranges from http://insight.typepad.co.uk/insight/team-building-games/ Creative Commons Graham Knox, Non-commercial, Non-derivative		

Table G.2 – Survival scores

A Summary of modifications to the paper based task is as follows:-

- 16 items not 15 (matches are normally given along with the dinghy)
- Items have a weight (made up) and users can chose any number of items up to a weight limit
- The weight limit chosen means they cannot chose the top-5 items (to encourage debate and discussion)
- Scoring is the cumulative experts rank of all selected items
- Duplicates are allowed but not covered in scoring.

Appendix H – Kolab Implementation Details.

This appendix provides detail of **Kolab**'s hardware and software realisation of the interaction design.

Hardware and Software Platform

Kolab uses a small number of off-the shelf components - A standard notebook PC and a commodity RGB-D sensor[Microsoft 2011] mounted on a tripod or stand.

For reference, **Kolab** was developed using Microsoft C/C++ in Visual Studio 2008, the OpenCV computer vision library v2.1 [Bradski 2008] and the Code Laboratories 'Kinect' Driver v1.0.0.1121 [retrieved from http://codelaboratories.com/nui in November 2010].

Kolab Software Structure

Kolab is a computer vision based system and as such needs to perform a number of operations typical to this technology, figure H1 below presents a flowchart of the main software tasks performed by Kolab. Each step is briefly explained to give an overview of how Kolab operates before giving detailed descriptions of key techniques and algorithms.

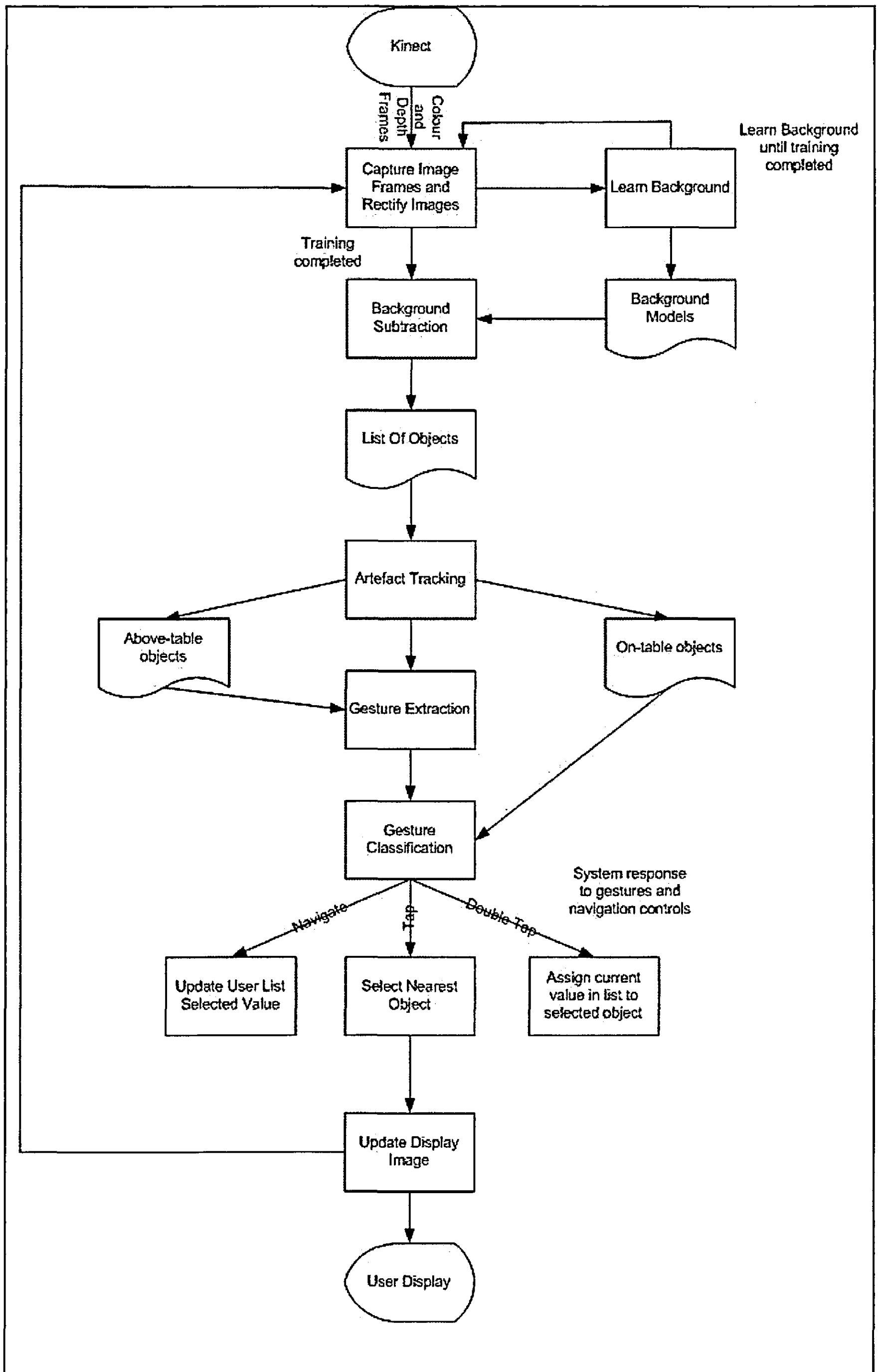


Figure H1 – Kolab software flowchart

Once the colour and depth images have been read and rectified to account for differences in the sensor positions relative to each other ;the next task is to extract out from the a scene the items of interest, the 'foreground' objects, and to ignore those that are not of interest, the 'background' objects. **Kolab** uses a technique called background subtraction to achieve this.

Kolab maintains a list of all foreground objects and splits them into two lists - 'tangible objects' on the surface representing data and controls and 'hands' above the surface. Each object is tracked across image frames to assign consistent labels to the objects in different frames. During the tracking process **Kolab** accounts for the occlusion by users' arms of objects on the surface using knowledge of the location of 'hands' from previous frames and estimates which surface objects are likely to be hidden from the camera by users, see later for more detail on object tracking.

In order to extract gestures from the input images the 'hand' objects are processed to establish the 'pointing part' and to which user it belongs to. The 'pointing part' may be a single finger or the whole hand and the path of this point is tracked across subsequent frames as described earlier. Gesture extraction is described further below.

When a gesture is completed the path of the finger is used as the basis for gesture classification and as a result of applying a classification algorithm **Kolab** triggers the relevant internal operation such as associating a digital value to a 'tapped' artefact or changing the selected item on the on-screen list of digital values (see Chapter 3 Interaction Design for an explanation of these).

Finally, **Kolab** maintains the internal state of the application and updates the feedback-image presented to users on the screen.

The main features of **Kolab**'s implementation described above are expanded upon in the remaining sections of this appendix.

<u>Capture and Rectify Image Frames</u>

Using the Microsoft Kinect [Microsoft 2011] gives **Kolab** a standard RGB camera image of the scene (referred to as 'the colour image') as well as an image that represents depth information (the 'depth' image). Each pixel in the depth image can be converted to a value in metres which measure the distance from the sensor to the detected object. Kolab uses a function from [Barras

2011] to achieve this. A brief explanation of how the two sensor images are used together is presented to clarify later use of x, y and z co-ordinates.

The two images come from two sensors mounted close together within the Kinect device and these images need correcting or rectifying in software so that there is a correspondence between the pixel at position (x,y) in the colour image and the pixel (x,y) in the depth image. Figure H2 below illustrates this problem. In this image notice that when the depth and colour images are placed side-by-side how features on each image are not aligned, for example the top of the person's head. **Kolab** uses a heuristically derived offset map applied to the depth image to achieve this.

Figure H2 –Unaligned images.

Unless specified otherwise references to the depth image will refer to the image that has been rectified with the colour image such that the depth (or 'z' value) of pixel (x,y) in the colour image is the value from the same (x,y) position in the depth image.

It is worth noting that the frame of reference differs between (x,y) and z dimensions. The (x,y) coordinates are co-ordinates of pixels in the colour image which is a standard 640x480 computer image. The 'z' value is a real-world value in meters measured from the depth sensor.

Background Modelling and Subtraction

During an initial training phase the system models pixel values from images of the surface when it is empty of tangible artefacts and users' hands. In the training phase **Kolab** constructs two statistical background models, one for the depth channel and one for the colour channel. The models are based on the assumption that the pixel intensity values in the background images are normally distributed and for each pixel its average value and average difference (a value which tracks standard deviation [Bradski 2008]) are recorded over the short initial training phase. This is often referred to as a 1-Gaussian background model [Bradski 2008] [Piccardi 2004] [Parks 2008].

[Wilson 2010] reports that noise from the type of depth sensor used in **Kolab** [Microsoft 2011] is not normally distributed and suggests a histogram based approach to model the characteristics of each pixel rather than a normal or Gaussian model. From user trials the interaction design was subtly changed to account for the small inaccuracies in **Kolab**'s modelling method by introducing a visual marker to show the calculated location of finger tips so that users could account for small errors in calculating hand position.

Once trained **Kolab** uses the two background models to examine each new set of input image frames (colour and depth) and extract out the items of interest, referred to as foreground objects. It does this by subtracting out the details of the background models from the new images, a technique known as background subtraction. This subtraction is done by comparing new image frames with the respective background model and, on a pixel by pixel basis, a decision is made to determine if the pixel represents 'foreground' or 'background'. The value of a pixel is compared to the modelled value and if outside a range defined by the average difference +/- the average value then it is classed as 'foreground'.

So, *Foreground(x,y) = [i(x,y) > mod (K d(x,y) + a(x,y))]* where *i(x,y)* is the measured pixel value, *K* is a multiplying constant, *d(x,y)* the average difference of the pixel values measured during the model construction and *a(x,y)* the average pixel value measured during the model construction.

The depth and colour channels are processed independently and the results are two binary masks in which a '1' indicates a foreground pixel and a 0 indicates a background pixel. After post-processing to remove noise these masks are then examined and the contours of each object are extracted using in-built OpenCV functions described in [Bradski 2008 chapter8]. A contour is a list of points that represents the edge of a connected set of pixels in an image and is an object's outline shape. By extracting out all of the large contours in the foreground mask images we extract out the location of each large foreground object.

An area threshold on each extracted object is applied to help reduce the impact of sensor noise and changes in ambient light. **Kolab** discards those objects with an area below a threshold of 300[3] pixels (approx 2.5*2.5cm) to remove noise objects and discards large contours over ½ the area of the image as this often suggests large shifts in light levels or high noise levels on the input image. This method of using contours has a knock-on effect on the overall use of the system as it imposes upper and lower limits on the size of objects that **Kolab** will accept on the surface.

The resulting foreground objects can then be processed for tracking. The process of tracking new objects is discussed next.

Artefact Tracking

The use of improvised tangibles means that **Kolab** can assume little about the sort of characteristics an object may possess in order to uniquely identify it when it is first introduced on to the surface and to subsequently track it across image frames as it is moved.

[Yilmaz 2006] defines a tracker as something that 'assigns consistent labels to the tracked objects in different frames'. Common tracking methods such as the Kalman filter or Camshaft tracking are limited to tracking single objects and as such not appropriate for Kolab which must track multiple objects both on and above the table, see [Bradski 2008] [Yilmaz 2006] for a discussion of these

[3] At 80cm above the surface 6pixels approximates to 1cm, on the surface

standard tracking techniques. For **Kolab**, a point based tracking system using an artefact's centre of mass tracked over subsequent frames was developed to handle the tracking of multiple improvised tangibles.

By 'point-based' we mean that each object is represented by a single point (x,y,z). The x and y positions are calculated as the position of the object's centre based on its contour extracted from the colour image (see above); the calculation of this central point, known its centre of mass, is described in Appendix K. The depth reading (z) is derived by taking the corresponding value at the (x,y) position in the rectified depth frame.

Each object is therefore represented by the vector *{x, y, z, bx1, by1, bx2, by2, vel_x,vel_y,vel_z}*. Where *x,y,z* together represent the position of the object's centre of mass and the depth reading at that point; *bx1, by1, bx2, by2* are the (x,y) co-ordinates of the object's bounding rectangle corners and *vel_x,vel_y* and *vel_z* are approximate velocities of the object in each direction. From this representation the vector for tracking is the vector (x,y,z), this is typically referred to as the *feature* vector. The velocity data are used to discriminate between moving and stationary objects to optimise the tracking and the boundary rectangle is used when estimating which objects are occluded.

Using this data each object is reduced down to a single point and that point is matched across frames using a 'nearest neighbour' search. An 'n-nearest neighbour' search, as the name perhaps suggests, attempts to search for n points that are by some distance measure closest to a defined start point. In the case of Kolab the search used is a 1-Nearest Neighbour search to match each tracked item from one image with the physically closest object in a new input image taking in to account all objects on the surface, occlusion and the physical movement of objects on the surface. The figure H3 below describes the basic operation of the tracking algorithm.

An algorithm for point based tracking of multiple objects using a 1-Nearest Neighbour search,

operating in $O(n^2)$.
For all tracked objects: if under the bounding rectangle of a moving depth object in the new frame then increment the object's lost count else reset lost count.
For all tracked objects not marked lost: Match to all possible objects in the new frame search space within set radius; search this subset for the nearest object that is no nearer another object being tracked. When matched, mark the tracked object as 'matched' and remove the corresponding object from the new frame search space.
Repeat above step for all unmatched tracked items removing the velocity (radius) constraint. This attempts to 'pick up' the objects being tracked that have moved beyond the radius.
For all tracked objects where the lost count exceeds a threshold, remove them.
For all new objects still remaining in the new frame search space assume they are new objects to track, add them to the tracked objects list and initialise them.

Figure H3 – Tracking algorithm

This tracking technique has an impact on the interaction design. By reducing an object down to a point representation based on its contour an object's contour cannot change significantly between frames, objects cannot therefore touch as they will be collectively recognised as a new single large object. By imposing a velocity or proximity constraint on the nearest neighbour search, objects are assumed to have limited motion between frames; as such objects need to be moved smoothly and slowly on the surface to be tracked successfully between frames.

The path that the 'hand' objects are tracked over is used to represent the gestures performed by users. The gesture extraction and recognition techniques used in **Kolab** are explained in the following sections.

Gesture Extraction

Sweeping and pointing

By using objects in the depth channel for gesture recognition the need to use colour based techniques such as skin segmentation to localise the hands within frames is removed instead any object in the depth channel that is connected to the side of the input image and above the table by a set threshold (5cm) is considered a candidate arm.

A heuristic was developed to determine the source of the gestures – using the connectivity of an arm's bounding rectangle to the image frame boundary Kolab determines which side the arm is coming from and therefore which user; by using the convex hull defects the general 'pointing' part of the arm can be extracted and tracked. The candidate fingertips are the peaks on the convex hull[4] [Bradski 2008]. The pointing tip is taken to be the location of the candidate fingertip furthest away from the centre of the arm shape's bounding rectangle and furthest away fróm the area connected to the frame boundary, similar to the method used by [Oka 2002]. This method is illustrated in figure H4 below.

[4] An alternative is template matching to find candidate fingertips which has been used extensively e.g.[Oka 2002], [Do-Lehn 2009b], [Crowley 1995], [LeTessier 2004]

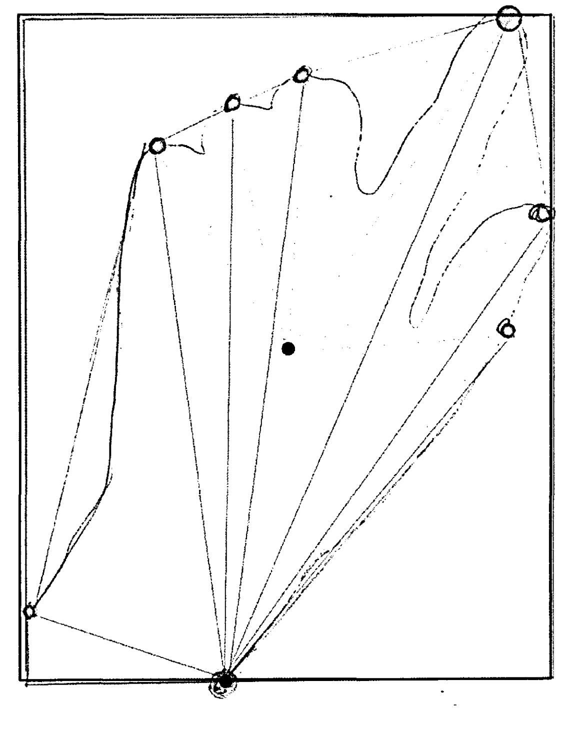


Figure H4: Fingertip extraction

Once extracted the fingertip is tracked as a point in the same manner as the TUI artefacts (discussed earlier).

[Pavlovic 1997] describes a gesture as three distinct phases: preparation, nucleus (the meaningful part) and retraction. As a side-effect of using the Kinect at such close range the system provides a space above the table for gesture preparation and retraction. The Kinect is not designed to operate at distances of less than 4ft (120cm) [Microsoft 2011] however in the Kolab set up this did not appear to be the case, giving a working range after only 60cm.This provides a 60cm ' dead zone' in which users could work above the table without registering movement (see figure H5 below).

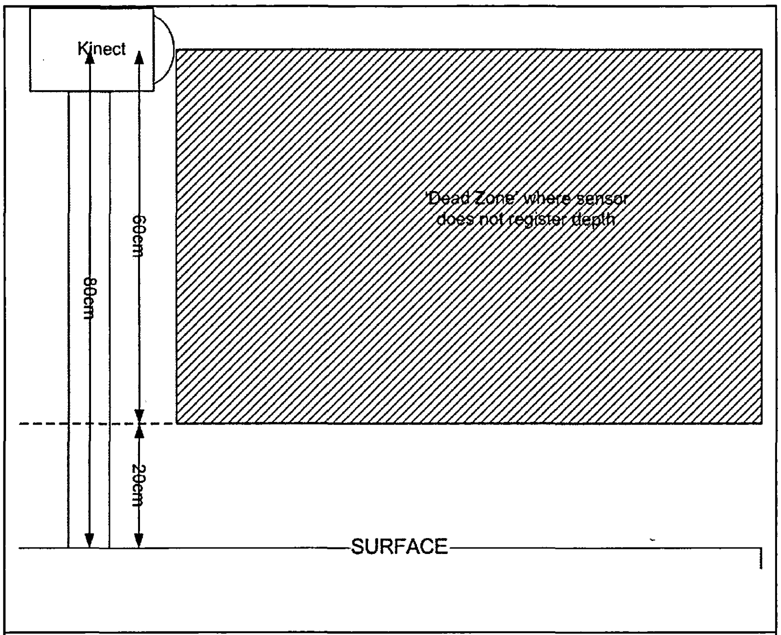


Figure H5 - Sketch Diagram of 'dead zone'.

Tapping Gestures

Work by [Wilson 2005] and [Dippon 2011] demonstrates how the Kinect may be used as the basis for a touch surface and this same concept is used to provide a touch based selection mechanism by using the height of the fingertip being tracked and detecting when it hovers close to or touches an artefact.

To detect which object is being tapped or touched a 16pixels (2.5cm) radius circle is applied around the calculated position of the fingertip to accommodate inaccuracies in the image rectification processes (section earlier). The nearest object to the fingertip within this radius is assumed the one selected. This allows for a lack of accurate stereo image rectification and inaccuracies in the depth sensor at close range.

Gesture Classification

Gesture classification is achieved by using a rule-based approach to classify the path of a tracked finger-tip built up from the point of introduction to retraction. The rationale for choosing a rule-based approach is that the gesture set is small and no off-line training phase is required unlike more complex probabilistic methods such as Hidden Markov Models [Rabiner 1989].

A finger tip is tracked (see above) and when retracted and tracking ends the path is normalised into a 10 point path fitting in to a 25x25 point space (see below) and then converted to an 8 point chain code [Lee 2010] [Loncaric 1998] by calculating the angle between each point of the normalised path. The direction of the start and end codes are analysed to indicate the general direction of travel. From this a sweep left or right or no gesture is determined.

To help filter out unintentional and other 'non-gesture' movements the length of the path traced by a tracked fingertip must exceed a minimum number of tracked points (7) before the path is normalised. The normalisation steps are based on the first steps of [Wobbrock 2007] excluding the rotation step as the direction of the gesture is significant within Kolab; first the raw data is converted into a path of a standard size (8 points for Kolab) and then scaled and translated so the points exist centrally in a 25x25 point space. In practical terms this meant an exaggerated sweep of the arm is required to register a valid gesture.

A Tap or Double Tap gesture is triggered if the tracked point of a hand (see above) is stationary close to or on the surface for 2 seconds (Tap) or stationary for two seconds, raised and returned within 1 second (Double tap). To account for noise and 'jitter' a point is considered stationary in the (x,y) direction if it does not move more than 20 pixels (3cm approx) between frames and 14mm in the z direction. The artefact 'touched' is the one nearest the fingertip point (see above).

Appendix I – Calculating the Centre of Mass using image moments.

The Kolab system describes each item it has to track by a single point with co-ordinates (x,y,z). This allows potentially heterogeneous objects such as improvised tangible objects introduced onto the surface and the fingertips used in gestures to be reduced to a common descriptive feature so that they can be tracked across subsequent image frames. Here we provide some background to describe the technique used to calculate the (x,y) co-ordinates of this point from an object's shape outline, this outline is also known as its contour. The 'z' value is retrieved from the depth reading at this calculated (x,y) point.

Using the contour of an object the centre of mass can be calculated from the spatial moments of the shape. Using the zero'th (M(0,0)) and first order (M(1,0), M(0,1)) spatial moments of the contour the centre of mass point (x,) can be calculated where x= M(1,0)/M(0,0), y=M(0,1)/M(0,0).

Where M(m,n) is defined as $\sum_j\sum_k x^m{}_k y^n{}_j P_{jk}$, the summation is performed for all rows and columns in the image so j, k are the row and columns, x_k and y_j are co-ordinates in the image, P_{ij} is the pixel value (1 if the pixel is on the shape's contour otherwise 0) and m,n are integers that define the moment order. A simple, worked, example of this calculation follows.

Example calculation of centre of mass of a simple shape contour

1 2 3 4

1

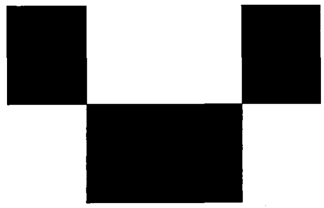
2

M(0,0)= 8

M(1,0)= 20

3

4



M(0,1)= 20

x= 2.5

y= 2.5

M(0,0)

X	0	Y	0	Pxy	calc	sum
1	1	1	1	0	0	
1	1	2	1	1	1	
1	1	3	1	1	1	
1	1	4	1	0	0	
2	1	1	1	1	1	
2	1	2	1	0	0	
2	1	3	1	0	0	
2	1	4	1	1	1	
3	1	1	1	1	1	
3	1	2	1	0	0	
3	1	3	1	0	0	
3	1	4	1	1	1	
4	1	1	1	0	0	
4	1	2	1	1	1	
4	1	3	1	1	1	

4	1	4	1	0	0	8

M(0,1)

X	0	Y	1	Pxy	calc	sum
1	1	1	1	0	0	
1	1	2	2	1	2	
1	1	3	3	1	3	
1	1	4	4	0	0	
2	1	1	1	1	1	
2	1	2	2	0	0	
2	1	3	3	0	0	
2	1	4	4	1	4	
3	1	1	1	1	1	
3	1	2	2	0	0	
3	1	3	3	0	0	
3	1	4	4	1	4	
4	1	1	1	0	0	
4	1	2	2	1	2	
4	1	3	3	1	3	
4	1	4	4	0	0	20

M(0,1)

X	1	Y	0	Pxy	calc	sum
1	1	1	1	0	0	
1	1	2	1	1	1	
1	1	3	1	1	1	
1	1	4	1	0	0	
2	2	1	1	1	2	
2	2	2	1	0	0	
2	2	3	1	0	0	
2	2	4	1	1	2	
3	3	1	1	1	3	
3	3	2	1	0	0	
3	3	3	1	0	0	
3	3	4	1	1	3	
4	4	1	1	0	0	
4	4	2	1	1	4	
4	4	3	1	1	4	
4	4	4	1	0	0	20

Appendix J – Kolab Performance during the user study

System Performance

In this appendix we review the performance of the prototype during the user study, the purpose of this section is to inform further iterations of Kolab and other similar developments.

System setup

For security reason the Kolab system was packed away at the end of each day of the study and setup again prior to user study sessions starting. This took less than 10 minutes and followed the same steps each day - the table was covered, the monitor placed at one end of the table centrally and the sensor rig placed on top of the monitor with the laptop moved on to a nearby cupboard to free up space. The seeded objects were then scattered under the monitor.

Once positioned the sensor was fine tuned to ensure that the control area on the output image matched with the end of the table. This was achieved with Kolab running and the sensors being moved whilst referring to the screen image.

The curtain was drawn over the large sash window to help control the ambient light level within the room and the room lights were switched on. As the day progressed the lighting level in the room changed as the curtain did not provide full blackout, the window faced east and as such the effect on the sensors was most significant in the morning sessions (see below).

During the study the table was often knocked or the cloth pulled, this caused the sensor rig to wobble slightly impacting the object extraction algorithms and registering multiple false targets.

With the sensors approximately 69cm above the surface the work area was 80cmx80cm (approx).

Processing Speed

The sensors delivered images of 640x480 pixels each. Running on a conventional laptop computer running Windows 7 Home edition, with no image processing the Kolab system captured images at

30 frames per second (fps), with full image processing and image tracking a frame rate of 20fps was measured. During the user study the Kolab system was used to record the surface for later analysis which reduced performance to between 12 and 14 fps. This was measured automatically by counting the frames processed in a run and the length of the run, when Kolab is terminated it reports the average frame rate. Whilst generally adequate for the study there was evidence of a lag between users moving an artefact and the tracked value 'catching up' on the output image.

Sensors

The MS Kinect [Microsoft 2011] with the Code Laboratory drivers[5] demonstrated some erratic behaviour during testing and the user study. At close range it would record extra 'shadows' in the depth image for example below the hand has 6 fingers. This resulted in the finger-tip extraction algorithm incorrectly identifying the pointing finger. The sensor would also develop a band where no depth data was recorded requiring a restart of the sensor.

This resulted in the failure of the gesture recognition system; attempts to tap or double-tap objects in a depth blind spot repeatedly failed, session#10 particularly suffered from this for one user.

The colour channel, in common with many computer vision systems, is sensitive to rapid changes in light and with a static background model (see Appendix H) sudden or significant changes in light levels caused by moving the sensor during operation, introducing reflective surfaces, shadows cast onto the surface by users and light bleeding through the room curtains created false readings in the channel. With multiple false targets the tracking failed and legitimate targets were lost in the noise requiring reprogramming by users.

[5] Official Microsoft drivers were not made available until June 2011

Multi-target Tracking

As well as sensor issues discussed above the tracking algorithm suffered from issues if users moved objects too fast across the surface or pick up items and moved them too far from the original position. If only a single object was move din this way then the matching process within the tracking algorithm often coped however if new objects (or false objects due to noise) were also introduced then tracking sometimes failed. These failures occurred in all sessions. The result of this issue was that the value of an artefact was lost and had to be re-associated by the participant. Generally a smooth sliding action worked best.

Navigation

When using TUI slider controls the implied spatial constraint of the 'control' area caused some initial confusion with users. Generally users needed to familiarise themselves with the location of the area on the table and refer back to the screen when sliding to ensure they stayed within the boundary of the area. As described above on a small number of occasions a user would over-reach and move a slider into their partners half of the table.

False objects (discussed previously) in the control zone also caused issues, effectively creating multiple controls for which the system was not set up. This resulted in random navigations being registered.

The ability to accurately track an object and the size of the object combined with the partitioning of the control area in to steps limits the usefulness of this technique. The 'step' size cannot be too small and this effectively limits the list length to about 20 items.

When the sweeping gesture was used the system made a number of false positive classifications of epistemic and non-interactive gestures for example extending the arm to point to an item to the side of a user resulted in a 'sweep' being detected. This caused some confusion for users as the system appeared to behave un-predictably.

Appendix K – Enlarged sample screen shot.